An evaluation of possible causes of the decline in pre-fishery abundance of North American Atlantic salmon

Edited by

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ABSTRACT

This document presents and describes 62 hypotheses for the decline in pre-fishery abundance estimates of Atlantic salmon of North American origin. Proposed hypotheses apply to six life stages (returning adult to egg, egg to hatch, hatch to smolt, smolt out-migration, ocean life, adult return through estuaries) in eight categories (fisheries, aquaculture, disease, predation, life history, chemical environment, physical/biological environment, thermal environment). The plausibility of each hypothesis was evaluated for salmon originating in 18 districts in Quebec, the Canadian Maritimes, and the north-eastern United States. Hypotheses were scored for Area (the proportion of habitat within each district affected by the hypothesized factor), Degree (the intensity of the hypothesized effect in the area where it applies), Magnitude (Area x Degree), and Trend (the degree of concordance between trends in the hypothesized effect, and changes in salmon populations). The 12 leading hypotheses, ranked by the product of Magnitude and Trend and weighted by egg conservation requirement for the district, included two hypotheses related to freshwater life and 10 hypotheses related to estuarine/marine life. However, one hypothesized marine mortality factor (that density-dependent effects in fresh water influence subsequent survival at sea) is based on a freshwater cause. Of the 12 top-ranked factors, five are related to predation, five are related to life history, one is related to fisheries, and one is related to the physical/biological environment. The reliability of the plausibility scoring system is constrained by inadequate knowledge, especially in the estuarine and marine phases. Nevertheless, the scores may serve to identify hypotheses at both local and international scales that are worthy of further investigation.

RESUMÉ

Ce document présente et décrit 62 hypothèses pour le déclin dans les estimés d'abondance pré-pêche des saumons de l'Atlantique d'origine nord-américaine. Les hypothèses proposées s'appliquent aux six stades vitaux (retour d'adulte à l'oeuf, oeuf à l'éclosion, éclosion au saumoneau, départ des saumoneaux, vie océanique, retour des adultes à travers les estuaires) dans huit catégories de facteurs (pêches, aquaculture, maladies, prédation, cycle vital, environnement chimique, environnement physique/biologique, environnement thermique). La plausibilité de chaque hypothèse a été évaluée pour les populations de saumons de 18 zones géographiques au Québec, des provinces maritimes du Canada, et du nord-est des États-Unis. On a assigné des cotes pour Superficie (proportion de l'habitat dans la zone qui est affectée par le facteur proposé), Degré (intensité de l'effet proposé dans l'habitat ou il s'applique), Importance (Superficie x Degré), et Tendance (niveau de concordance entre les tendances dans l'effet proposé et les changements dans les populations du saumon). Les 12 hypothèses les plus fortes, classées selon le produit de l'Importance et Tendance et pondérées par le besoin d'oeufs pour conservation dans la zone, se répartionnaient en deux hypothèses pertinentes à la vie dulcicole et 10 hypothèses pertinentes à la vie marine. Cependant, un facteur de mortalité marine (que les effets de la dépendance de la densité influent sur la survie en mer) est basé sur une cause en eau douce. Parmi les 12 facteurs les mieux cotés, cinq sont reliés à la prédation, cinq au cycle vital, un à la pêche, et un dernier à l'environnement physique/biologique. La fiabilité du système d'évaluation de la plausibilité est contrainte par les connaissances inadéquates, surtout pour les stades estuariens et marins. Malgré cette contrainte, les cotes peuvent servir à identifier les hypothèses à l'échelle locale et à l'échelle globale qui méritent des études plus approfondies.

INTRODUCTION

Estimated numbers of Atlantic salmon of North American origin prior to any fishery have decreased by about one half to two thirds since the early 1980s (Anon. 2000, Potter and Crozier 2000). This decline has caused concern among anglers, conservationists, and biologists, and raised anxieties about the future of wild salmon in the northwest Atlantic.

A necessary prerequisite to the reversal of this decline, if such is possible, is understanding its cause. Aquaculture, disease, river blockages, pollution, unreported fishing, predation, food supplies, and ocean conditions have been proposed as contributing factors to the decline (Dempson et al. 1998, Anon. 1999c, Dempson and Reddin 2000). However, there is no clear evidence linking any of these factors to the overall decline and the cause or causes of the decline remain unknown.

In June 2000, an international workshop was held at Dalhousie University in Halifax to develop research strategies to determine the cause or causes of the decline in pre-fishery abundance. Deliberations and conclusions of this workshop are summarized by O'Neil et al. (2000). The present document was originally prepared as background material for the Dalhousie workshop. Its purpose is to present a comprehensive list of potential causes of the salmon decline, to summarize the main features of each hypothesized cause, and to evaluate the plausibility of potential causes on a district-by-district basis. The overall goal is to identify hypotheses which are plausible, thereby helping guide researchers to avenues of investigation that have the best chance of success.

In addition to the pressures which have caused the decline in pre-fishery abundance, North American Atlantic salmon also face future changes in their thermal environment due to global climate change. Any long-term Atlantic salmon recovery plan will have to take these shifts into account. This paper outlines predicted impacts on salmon of climate change.

This project was a co-operative venture involving Canadian federal, Canadian provincial, U.S. federal, and U.S. state biologists. Individual factor accounts were reviewed by other authors of other factor accounts, and the whole document was subject to three comprehensive reviews. Contributors and their affiliations are listed in Appendix A. The plausibility analysis covers salmon originating in Quebec, Canadian Maritime, and New England rivers. Causes of low returns to Newfoundland and Labrador rivers have been examined elsewhere (Dempson and Reddin 2000).

METHODS

The list of factors hypothesized to cause the decline in Atlantic salmon pre-fishery abundance was generated by diadromous staff of Gulf, Maritimes, and Headquarters Regions of the Department of Fisheries and Oceans, on the basis of literature (Anon. 2000, Dempson et al. 1998, many others), personal knowledge, and discussions with biologists from other jurisdictions. Factors were classified according to six life stages (I - returning adult to egg, II - egg to hatch, III - hatch to smolt, IV - smolt migration through rivers and estuaries, V - ocean life, VI - adult return through estuaries), and eight impact categories (1 - fisheries, 2 - aquaculture, 3 - disease, 4 - predation, 5 - life history, 6 - environment (chemical), 7 - environment (physical/biological), 8 - environment (thermal)).

Sixty-two factors that potentially contribute to salmon mortality or constrain reproductive success were catalogued. Two predictions arising from climate change projections were also enumerated. Accounts for each factor present the formal hypothesis or prediction, a summary of background information, an assessment of whether the factor operates in a density-dependent or density-independent manner, a statement of the geographic scope over which the factor operates, a summary of changes in the intensity of the factor since 1984, a summary of the evidence for and against the factor, a description of possible hypothesis tests, a prediction of future consequences to salmon if the hypothesis is true, and an evaluation of potential methods and chances of success of human intervention to eliminate or reduce the factor.

Plausibility of hypothesized factors was scored for each Salmon Fishing Area (SFA) in the Maritime Provinces of Canada, and for districts in Quebec and New England (Fig. 1). Predictions arising from climate change projections were not scored. Scores were assigned by assessment biologists responsible for each district. Each factor in each district received three direct scores and one derived score. Scores reflect the situation between 1984, when the current decline in returns began, and 1999. The Area score is the proportion of salmon habitat within the district where the hypothesized factor affects salmon survival or reproductive output. For factors operating in the marine environment that potentially affect all salmon originating in the district, the Area score is 1.0. The Degree score indicates the intensity of the hypothesized factor in constraining salmon survival or reproductive output in the habitat where the factor operates. Degree scores range from 0 (no effect) to 1.0 (drastic effect). The Magnitude score is the product of the Area score and the Degree score. The Magnitude score reflects the overall impact of the hypothesized factor on the survival or reproductive output of salmon in or from the district. The Trend score indicates the concordance of changes in the hypothesized factor with changes in salmon returns for the period 1984-1999. A positive Trend score indicates that the factor has intensified in the period 1984-1999. Hence if the factor has impact on salmon survival or reproductive success, this impact would have increased between 1984 and 2000. A negative Trend score indicates that the factor has weakened between 1984 and 1999, so that any constraining effect it might have on salmon survival and reproductive output would have diminished over this period. Trend scores range from 1.0 to -1.0. A score of 1.0 indicates a large increase in intensity of the factor in 1984-1999, a score of -1.0

means a large decrease in intensity of the factor, and a score of 0 means no change in intensity of the factor.

The potential to produce salmon depends on available rearing habitat, which varies greatly among districts. Egg requirements for conservation, based on 2.4 eggs 100 m^{-2} of rearing habitat (O'Connell et al. 1997), reflects production potential. Overall scores for the various factors were calculated from raw summations, and also from summations weighted by egg requirements for conservation.

FACTOR ACCOUNTS

I. RETURNING ADULT TO EGG

I.1. Fisheries

I.1.a. Fishery removals in estuaries and rivers (L. Marshall)

Hypothesis - Total harvests by recreational fishers, poachers and aboriginals have increased, thereby reducing escapement and the ratio of spawners to returns.

Background – The closure of many commercial salmon fisheries in Canada and reduced quotas in Greenland might have resulted in increased returns to home rivers and increased harvests in recreational, aboriginal and illegal fisheries.

Density dependence - Largely density independent, although fishing effort would likely decrease significantly as catch approaches zero.

Geographic scope - May affect salmon throughout its range in eastern North America. Effects are likely to be more intense in densely populated areas.

Probable change since 1984 – Reported and unreported harvests have greatly decreased (Anon. 1999a) thereby contributing to an increase in the ratio of spawners to returns. Harvests have diminished because of curtailment or closures of recreational fisheries (DFO 1999a). Reporting of catches has improved because of co-operative fishing agreements with aboriginals, increased partnerships with other stakeholders working towards conservation objectives, and a more focused effort by fishery protection officers on a diminishing resource.

Evidence – No evidence that local removals have increased in recent years.

Tests – Examine pre- and post- 1984 harvest statistics, ratio of hook-and-release / total caught recreational fish, ratio of spawning escapement / returns, densities of age-0+ fry abundance and returns estimates comprised of counted and tagged fish for an indication that returns are being consistently underestimated.

Consequences if true - Salmon declines will continue to the point where catch rates, and subsequently effort, will decline.

Potential for intervention – Closure of fisheries, increased surveillance and monitoring of illicit fisheries.

I.1.b. Hook-and-release mortality (L. Marshall and G. Chaput)

Hypothesis - Hook-and-release mortality is more significant than currently estimated and has increased over time and reduced the proportion of returns that spawn. Hook-and-release fisheries result in metabolic and physiological stress to fish which negatively affects their migration and spawning behavior.

Background – In 1984, fisheries managers imposed hook-and-release regulations on large salmon in the recreational fishery to reduce fishing mortality and increase egg depositions. More recently, hook-and-release fishing has been promulgated on small salmon of some area rivers and voluntarily practiced on small salmon of many other rivers (DFO 1998b). However, there is evidence that hooked-and-released salmon drop downstream after being angled (Chaput et al. 1998b) and that injured salmon spawn in less than optimum habitat and dig shallower redds than uninjured fish (Berg et al. 1986). Hypothesized increased occurrences of low water and high temperature situations could contribute to increased stress and an even lower spawning viability of released fish.

Density dependence – Largely density independent until such time as catch approaches zero and effort dissipates.

Geographic scope - May affect salmon throughout its range in eastern North America. Effects are likely to be i) most intense where there is significant fishing effort and some form of a retention fishery and ii) least intense where effort is minimal (perhaps due to remoteness) and / or retention of catch is not discouraged. Intensity of effects will be greater in areas where water temperatures are high during the fishing season.

Probable change since 1984 - On a Canadian scale, hook-and-releases angling has increased; in the Maritime provinces, numbers of hook-and-release fish have been decreasing consistent with decreased effort resulting from season and within-season closures.

Evidence – Seasonal and temperature limitations to survival of hook-and-release fish are addressed in DFO (1998b). The increasing proportion of hook-and-release caught fish among total caught fish in the Maritimes, declines in each of catch, hook-and-release catch, and effort (e.g., NS and NB) because of fewer returns/more restrictive management measures (including closures during periods of high water temperature) (Anon. 1999a) suggest potential for reduced mortality attributable to hook-and-release fishing in recent years. Low water temperatures reduce the risk of hook-and-release mortality (DFO 1998b). This is recognized in the recent imposition of daily opening and closing times. In areas where hook-and-release fisheries operated for a period of time and then all fishing was banned, there was no rebound of salmon numbers. This suggests that mortality due to hook-and-release has not been a major contributor to declines.

Tests - Largely conducted and synthesized and indicating that hook-and-release mortality is significantly less than hook-and-retain mortality (DFO 1998b). Behavioural effects of hook-and-release angling remain largely undocumented. Field experiments would be required.

Consequences if true - Salmon declines will continue until angling fisheries are closed completely. Reduced spawning success resulting from behavioural effects of hook-and-release angling will result in reduced juvenile production per spawner and the impression of lower freshwater productivity.

Potential for intervention - Closure of rivers to all angling or change to retention fisheries only.

I.2. Aquaculture

I.2.a. Returning adults which carry aquaculture genes, and their descendants, are less fit than fish of pure wild origin. (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - Survivorship among the offspring of "wild" fish carrying aquaculture genes is lowered due to loss of genetically adaptive characteristics, potentially lowering recruitment and population size.

Background - Farm origin salmon have been reported in 14 rivers in New Brunswick and Nova Scotia since the aquaculture industry began in 1979, with the highest level being reported from the Magaguadavic River, where 90% of returnees in 1994-1995 were farmed fish. Numbers of escapees are greatest in rivers located near the aquaculture industry, and escaped farmed salmon have been observed in the spawning stocks of some inner Bay of Fundy rivers (DFO 1999b).

The impact of escapees entering some Norwegian rivers has been significant where the farm-origin fish have accounted for over 70% of river entrants. Farmed salmon have been observed to spawn and interbreed. Escaped salmon are much more prevalent in the south of Norway where the industry is concentrated (DFO 1999b).

Spawning success by escapees has been well documented in Europe. Negative impacts could result from genetic changes that are likely to affect the survival or competitive abilities of offspring (Gross 1998).

Evidence from both North America and Europe suggests that the culturing of fish over several generations leads to important genetic changes in fitness-related traits (e.g. increased growth rate, altered aggression, and reduced response to predators). These changes, implanted in a significant proportion of wild fish through introgressed aquaculture genes could affect survivorship and result in reduced recruitment of wild populations (DFO 1999b).

Density dependence - Density independent.

Geographic scope - Narrow. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and rivers in which escapees occur in significant numbers are located near the industry.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada since 1981 to about 20,000 t in 1999.

Evidence - In Norway and Ireland, farmed salmon have been observed to spawn and interbreed. In New Brunswick, cage-reared adults have successfully spawned in the Big Salmon River and have been observed spawning in the Magaguadavic river (Carr and Anderson 1997). There is no documented Canadian evidence of wild-farmed spawnings having lower spawning success than wild-wild spawnings, but it is likely considering the Norwegian observations of Fleming et al. (1996) that farmed females carry more unspawned eggs, have more nest destruction, greater egg mortality, and overall have less than one third the success of wild females. Farmed males have fewer spawnings, often do not ejaculate, and overall have less than 3% of the success of wild males in Norway. In Norway, aquaculture fish that enter freshwater to spawn are only 16% as productive as wild fish in production of returning adults (Fleming et al. 2000).

The likelihood that wild stocks are adapted to their local environments makes it highly unlikely that the impact of farmed escapes will be positive. Current understanding is insufficient however, to specify the precise nature and degree of negative impacts that can be expected. As the environmental and genetic circumstances of each situation will be unique in many ways, each outcome will be also be unique (DFO 1999b).

Some generalizations are possible. In circumstances involving small numbers of escapees derived from a local stock in the presence of abundant local wild stock, the effect could be negligible and genetic changes may be countered through natural selection. Generally, impacts can be expected to increase with the degree of genetic and non-genetic differences, the degree of ecological overlap, and the extent of interbreeding. In the extreme, the outcome of an interaction could be the elimination of the self-sustaining wild stock (DFO 1999b).

Tests - Given the difficulties of advancing understanding through empirical studies, increased insight into the outcome of genetic introgression from aquaculture salmon might be derived from improved dynamic models, which consider how different variables interact to affect the outcome (DFO 1999b). In extreme cases where wild populations have nearly disappeared, analysis of original genetic material (if available) and comparison with present hybrid genetic material may provide evidence that the original genetic stock has been substantially replaced. If the hybrid stock is maladapted and not thriving, this would provide local evidence for the hypothesis.

Consequences if true - Wild populations in rivers located near the aquaculture industry will continue to decline as long as escapement continues.

Potential for intervention - Improved containment would lower the risk of escapes. In 1997, DFO, in consultation with provincial authorities, industry, manufacturers and insurers, drafted a document entitled "Code of Practice for the Containment of Non-local Strains of Salmonids in Sea Cage Culture in the Atlantic Provinces." The proposed code of practice specified standards for nets, cages, moorings, fish handing, and contingency measures. This code has not been adopted. Effective containment standards would require an audit system to ensure compliance (DFO 1999b).

Other interventions to reduce the potential for interaction between wild and farmed stocks include: selective siting of farms and hatcheries, use of local stocks, sterilization of farmed fish, enhanced training and education of aquaculture workers, improved escapement reporting, recapture of escapees, improved containment of aquaculture juveniles and blocking river entry of farmed fish (DFO 1999b).

I.2.b. Aquaculture escapees compete with wild fish for spawning sites (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - Mature aquaculture escapees compete with wild fish for spawning sites, and reduce spawning opportunities for wild fish through direct displacement, or reduce their reproductive success through nest superimposition.

Background - Farm origin salmon are commonly found in rivers close to areas of concentration of the salmon aquaculture industry (see I.2.a).

Successful spawning by escapees has been well documented in Europe, where there is also clear evidence of negative impacts resulting from the destruction of eggs spawned by wild salmon as a result of nest superimposition by escaped farmed females (Webb et al. 1991, Gudjonsson 1991).

Density dependence - Density dependent. Both the density of wild adults and aquaculture escapees in spawning habitat affect the possibility of this interaction between wild and farmed fish.

Geographic scope - Narrow. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and escapees only occur in significant numbers in rivers located near the industry.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada, with current annual production of 20,000 t annually.

Evidence - In New Brunswick, adults of aquaculture origin have successfully spawned in the Big Salmon River and have been observed spawning in the Magaguadavic river (Carr and Anderson 1997). There is no documented evidence that competition with wild fish for spawning sites has been a major factor in wild population declines in rivers adjacent to the Canadian aquaculture industry and escapees are not present in spawning habitat in most Northwest Atlantic rivers (DFO 1999b).

Tests - Field surveys to detect possible competition for spawning sites.

Consequences if true - Wild populations in rivers located near the aquaculture industry will continue to decline as long as escapement continues.

Potential for intervention - See I.2.a.

I.2.c. Hatchery-reared salmon have lower spawning success than wild salmon (G. Chaput and L. Marshall)

Hypothesis - Hatchery-origin fish have lower spawning success than wild fish because they may be unable to respond appropriately to environmental cues.

Background – Fish reared in culture, then released to a natural stream environment, may yield fewer effective spawning adults than wild bred salmon (White 1995). Thus the advantage in numbers of offspring gained by hatching eggs in captivity and rearing young to release may be lost after release, i.e., fewer effective spawners result than if the parents had been allowed to spawn naturally. Release of fish in streams to which they are not genetically adapted, and inbreeding of spawners, may contribute to these effects.

The hypothesis implies that i) hatchery activity has increased, ii) that hatchery practices are ignoring the three- to four- decade old stock concept (river-specific collections and stocking), or iii) that continuous stocking of specific stocks on top of their wild-source populations has gradually extended a lessening of genetic adaptiveness and fitness through the entire population.

Density dependence - Density independent.

Geographic scope - Can affect salmon only in the southern portion of the range i.e. New England, some parts of the Maritime provinces and the more populated areas of the north and south shores of the St. Lawrence River where there are hatchery based enhancement programs.

Probable change since 1984 - Unlikely to be a change in the impact on wild populations where broodstock removals are stock specific, or of negligible size relative to the total population. Also unlikely to impact wild populations where hatchery products, especially, juveniles, but including smolts, are released to prime habitat in their river of origin. However, there may be a possibility of change where broodstock removals are a substantial fraction of the population, or are not stock specific and where adults stocked as smolts lack cues for the selection of appropriate spawning areas.

Evidence - There is no documentation that hatchery practices have contributed to declines of Atlantic salmon in eastern Canada. Recent DNA/microsatellite studies suggest that genetic diversity is maintained through at least several generations of smolt stocking and resultant spawning among their wild counterparts (McConnell et al. 1995). Genetic diversity has, however, been compromised or extended in other specific cases (Busak and Currens 1995). There is also a suggestion that adults originating from hatchery-reared smolts may spawn in locations that are later subject to de-watering, severe ice scouring etc., and yield fewer recruits per spawner than wild salmon using successful natal spawning areas. This effect could manifest itself as a reduction in recruits per spawner with declining abundance of wild populations.

Tests - Compare trends in returns of wild salmon in enhanced and unenhanced populations; comparatively evaluate redd selection sites and egg survival data from wild and hatchery females spawning in the same system.

Consequences if true - Inappropriately designed hatchery stocking programs could result in initiation or continuation of declines of wild salmon.

Potential for intervention - Careful planning of hatchery programs for mitigation, development and restoration with focus on stocking of progeny into the natural environment at the youngest life stage possible.

I.2.d. Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - Mature aquaculture males and females may be inadequate mates for wild fish. Aquaculture females may select inappropriate sites for redds, and males may not react normally to mature wild male parr, affecting spawning success.

Background - Farm origin salmon are commonly seen in rivers close to areas of concentration of the salmon aquaculture industry (see I.2.a).

Density dependence - Density independent.

Geographic scope - Narrow. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and escapees only occur in significant numbers in rivers located near the industry.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada, with current annual production of 20,000 t.

Evidence - In Norway, farmed salmon have been observed to spawn and interbreed. In New Brunswick, cage-reared adults have successfully spawned in the Big Salmon River and have been observed (Carr and Anderson 1997) spawning in the Magaguadavic River. There is no documented Canadian evidence of wild-farmed spawnings having lower spawning success than wild-wild spawnings, but it is likely considering the Norwegian observations of Fleming et al. (1996) that farmed females carry more unspawned eggs, have more nest destruction and greater egg mortality, and overall have less than one third the success of wild females. Farmed males have fewer spawnings, often do not ejaculate, and overall have less than 3% of the success of wild males in Norway.

Tests - Field behavioural studies would be required to determine whether location and construction of and spawning in redds is less successful for wild-farm than wild-wild matings.

Consequences if true - Wild populations in rivers located near the aquaculture industry will continue to decline as long as escapement continues.

Potential for intervention - See I.2.a.

I.3. Disease

I.3.a. Naturally-occurring disease (G. Chaput)

Hypothesis - Naturally-occurring diseases result in mortalities of adult salmon between the entry to freshwater and spawning.

Background - Numerous disease-causing agents have been identified in wild Atlantic salmon (Bakke and Harris 1998). These include *Renibacterium salmoninarum* (bacterial kidney disease (BKD) causing agent), *Aeromonas salmonicida* (furunculosis), infectious pancreatic necrosis virus, *Vibrio anguillarum*, and *Edwardsiella tarda* (DFO 1999b). There is a documented history of some of these diseases in Maritime rivers, including furunculosis in the Restigouche River and BKD in the Margaree River. Furunculosis is prevalent on both sides of the Atlantic (Roberts 1998). It was confirmed in 1997 from adult salmon of the Miramichi River and the Nashwaak River (Chaput et al. 1998b, Marshall et al. 1999). Furunculosis can become an important factor in adult in-river survival especially during periods of low and warm water conditions. Furunculosis can be spread by transfers of infected fish or natural movements of pathogen-bearing fish between rivers. There can be a large number of adult losses (Johnsen and Jensen 1994). BKD was also recently confirmed from the Miramichi (Chaput et al. 1994). A new disease agent, infectious salmon anemia virus (ISA), was discovered in aquaculture reared fish in 1997 (DFO 1999b).

Density dependence - Density dependent but can be aggravated by density independent factors (I.7.c, I.8.a).

Geographic scope - Diseases are of wide concern.

Probable change since 1984 - The recent diagnosis of the furunculosis-causing agent in the Miramichi and Nashwaak rivers in 1997 and the occurrence of ISA in aquaculture salmon suggests that the potential for disease to constrain on adult spawner survival may have increased.

Evidence - BKD in reconditioning kelts in the Miramichi 1993, furunculosis in Miramichi and Nashwaak in recent years, ISA in aquaculture fish. However, juvenile population densities in many rivers have thus far remained moderate to high, suggesting that disease is not a widespread problem at that stage.

Tests - Compare relative egg to juvenile survival rates over time. Egg deposition estimates would be unadjusted for known disease losses.

Consequences if true - If the hypothesis is true, escapement estimates would be overestimated and river production would be underestimated. Would result in reduced juvenile recruitment, followed by reduced adult returns.

Potential for intervention - Limited potential for intervention except at trapping facilities where antibiotics and vaccines can be introduced. Better long-term strategy is to allow a natural resistance to develop.

I.3.b. Disease transmitted from captive or escaped aquaculture fish (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - The expansion of the aquaculture industry has led to increased infection levels of endemic diseases or the introduction of exotic diseases among wild salmon. Sea lice have been suggested as a mechanism of cross contamination.

Background - Fish diseases were detected in wild salmonid populations as early as the beginning of the 20th century. Evidence from the West Coast of North America and Europe has shown that diseases identified in wild populations have impacted cultured stock with the reverse also occurring on rare occasions (DFO 1999b). One example of the latter is the transfer of furunculosis from farmed Atlantic salmon to wild fish populations in Norwegian rivers. The disease had been transferred in live aquaculture fish from Scotland to Norway (Gross 1998, Bakke and Harris 1998).

Density dependence - Density independent. Transfer to wild populations would likely require wild fish to be in proximity to the industry, or for escaped aquaculture fish to migrate into wild fish habitats.

Geographic scope - Narrow for direct disease transmission within rivers. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and aquaculture escapees are generally found only in rivers close to industry sites. However, marine movements of aquaculture escapees are poorly known and aquaculture escapees may range more broadly than has been recognized. In addition, it is possible that wild salmon infected by contact with diseased aquaculture fish might transmit diseases to other salmon during their long-distance migrations.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada, with current production of 20,000 t annually.

Evidence - Farmed salmon production in the Maritimes and the time series of sea survival data for three hatchery-reared wild stocks (LaHave and Liscomb, Nova Scotia, and Saint John, New Brunswick) are not significantly associated (DFO 1999b). There are no long-term measurements of sea survival for wild salmon stocks in the Maritimes. Also, there are limited data on disease prevalence, and trends in farmed and wild finfish populations in relation to disease prevalence have not been assessed. There is no evidence that, in the Maritimes Provinces, diseases of farmed fish have had an impact on wild fish or vice versa (DFO 1999b).

Tests - Improve sampling of wild and aquaculture populations so that existence of and trends in disease prevalence can be analyzed.

Consequences if true - Salmon declines will continue until wild stocks evolve resistance to problem diseases.

Potential for intervention - Negative effects can be reduced by producing healthy farmed salmon. Various initiatives are being developed to reduce potential fish health problems on fish farms including: adoption of codes of practice by the industry, provincial initiatives to develop and implement fish health programs, and at the federal level, the revision of the Fish Health Protection Regulations. Various additional requirements to strengthen existing fish health programs include: adequate compensation in cases where fish have to be destroyed due to an exotic disease, development of more sensitive diagnostic tools, disease surveillance of wild stocks, and mandatory reporting of exotic diseases. It is recognized that the lack of approved therapeutants restricts the ability of farmers to manage the impact of diseases (DFO 1999b). See also I.2.a.

I.7. Environment - physical/biological

I.7.a. Barriers to spawning migration (L. Marshall and D. Caissie)

Hypothesis – Barriers such as hydroelectric and water storage dams (without fish passage or with fish passage facilities that have deteriorated over time), beaver dams, log jams, road culverts (usually in concert with forest harvesting or flood followed by drought events, dewatering etc.), are increasing or have reduced fish passage efficiency and allow fewer adults than previously to access spawning areas.

Background – Small hydroelectric facilities have recently been encouraged within some jurisdictions, thereby reducing the certainty with which salmon will reach their spawning areas. Significant numbers of important older fish passage facilities require efficiency testing and invariably, repairs and upgrading. Low stream discharges or flow attraction at fishways can limit upstream migration and in the case of several very low water years in the 1990s, can discourage salmon from completing their migration.

Density dependence - Density independent. In isolated cases, there may be some density dependence if spawners denied access to their former habitat superimpose their redds in "home" areas of other spawning salmon, or choose marginal and possibly unproven spawning areas.

Geographic scope - May affect salmon throughout their range but is more problematic in developed, deforested, or poorly-managed forest areas within watersheds of the southern part of the salmon's range.

Probable change since 1984 - Unlikely to be a significant change because of the paucity of new dams, enforced legislation re: provision of fishways at permanent barriers and increased interest and participation by organized watershed groups partnering in the maintenance/ enhancement of fish passage and declining stocks of Atlantic salmon.

Evidence – There is little evidence to suggest that barriers to spawning migration or that fish passage efficiencies have diminished since 1984. River discharges would first have to be shown to be declining in recent years. In contrast, efficiencies of fishways are better understood (Clay 1993), and passage facilities are being reviewed (relevant to relicencing of hydro operations in some jurisdictions) and upgraded by power utilities. There have been few new hydro developments since 1984. Active watershed groups focusing on habitat and fish issues (i.e., flagging of nature-made obstructions) have increased in number and activity in the last 15 years. New technologies have been advanced and deployed for improved passage through road culverts (Conrad and Jansen 1996).

Tests - Quantification of relicencing efforts and improvements, new dams built, changes in hydrological effects of forest harvesting that might contribute an increase in natural barriers, replacement of old culverts, etc.

Consequences if true - Salmon declines will continue in the more populated areas of the salmon's range.

Potential for intervention - Removal of obstacles including dams, assessment and potential improvement of fish passage, deployment of culverts incorporating pools etc.

I.7.b. Spawning habitat is limited (G. Chaput)

Hypothesis - Spawning habitat is limited, leading to competition for spawning sites, redd superimposition, and use of sub-optimal habitat for egg deposition, resulting in lower egg to fry survival.

Background - Spawning habitat for Atlantic salmon has been described as areas of gravel in riffles above pools with average column water velocities above 20 cm per second (Gibson 1993). However, salmon may also spawn in atypical habitats and use of such locations increases the possible amount of spawning habitat. Substrate composition is of the type that favours the flow of oxygen and removal of egg metabolites and that prevents entombment of the eggs. High densities of spawners may result in redd super-imposition in favourable habitat or displacement of spawners to sub-optimal habitat. Natural and artificial barriers may also limit access to spawning habitat. Acidity also constrains spawning habitat.

Density dependence - Density dependent. Can be aggravated by density-independent factors such as discharge, sedimentation, and acidity.

Geographic scope - Spawning habitat has been quantified in only a few Maritime rivers. Conservation requirements are based on total wetted surface area or habitat for spawning and rearing. The simplest assumption is that spawning habitat is limiting.

Probable change since 1984 - Spawning habitat can be degraded by human activity such as road building, forestry exploitation, agricultural practices. Increased variability in hydrology and changing land use (forestry, agricultural and others) could be responsible for an increasing number of hydrological events which would reduce the amount of spawning habitat.

Evidence - Low egg-to-fry survival in Catamaran Brook following restricted and dense spawning of fish below a beaver dam (Cunjak and Therrien 1998).

Tests - Mapping redd distributions or young-of-the-year distributions relative to varying numbers of spawners to assess spawning habitat use.

Consequences if true - If the hypothesis is true, then salmon abundance would be constrained to an upper limit. If spawning habitat is now reduced from historical levels, the upper limit would have also been reduced.

Potential for intervention - If changes in quantity of spawning habitat are anthropogenic, then mitigation to reclaim or protect these habitat can be considered.

I.7.c. Alterations to discharge patterns reduce access to spawning areas (D. Caissie and D. Cairns)

Hypothesis –Flow alterations due to dams, other artificial obstacles, water withdrawal and land use practices reduce the access of adult fish to spawning areas.

Background - Natural flow regime is important for rivers (Poff and Ward 1989, Poff et al. 1997). Flow regimes in rivers can be altered by dams and other control structures, diversions, and withdrawal of water for municipal, industrial or agricultural use. On impounded systems, flow releases from dams are essential during low water conditions to protect fish habitat (Caissie and El-Jabi 1995, Reiser et al. 1989, Wesche and Richard 1980). Fluctuations may be dampened by dams and control structures, but fluctuations may also intensify if power dams alter their intake levels in response to short-term variation in electricity needs (hydropeaking). Hydropeaking can adversely affect aquatic habitat (Valentin et al. 1995). Removal of forest cover for logging or agriculture tends to increase discharge fluctuations and increases the frequency of flooding. Extraction of water for irrigation (such as with blue berry farmers in Maine) could also reduce flow regimes especially in dry years.

Fish need water to migrate. If water levels are insufficient, upstream movements may be halted. If discharge is too great, fish may be carried downstream. Adult Atlantic salmon enter rivers in North America between late spring and fall. Summer is normally a low flow period, and in some years low flow conditions may persist to autumn. If river levels are further reduced at this time because of anthropogenic flow alterations, upstream migration to spawning grounds may be impeded.

Density dependence - Density independent.

Geographic scope - In general, anthropogenic effects on flow regimes are greatest in the southern, more populated part of the salmon's range.

Probable change since 1984 - Most dams on salmon rivers were constructed prior to 1980. There has been an increasing tendency for power utilities to manage flow rates to mimic natural conditions. However, there are also pressures on utilities to maximize production from hydro plants to respond to increasing electricity demand. Water withdrawal has probably increased. There have been widespread forestry operations in watersheds of salmon rivers since 1984, but forestry practices that reduce rapid water run-off (riparian buffer zones etc.) have been implemented in some areas. Overall, there is probably little net change in the degree to which flow regimes in salmon rivers have been altered by human activities.

Evidence - There have been no systematic surveys of the extent to which upstream migration of salmon has been held back by low flows, due to either natural or anthropogenic causes. Although the majority of salmon entering eastern North American rivers do so in spring and summer, salmon do not spawn until fall. This means that salmon which are barred from rivers by low summer water can wait in the estuary or the lower river until the fall when rising water levels given them access to their spawning grounds. It is possible that fish that are held back in this manner have a decreased chance of reaching their spawning grounds and successfully spawning, but this has not been tested.

In years when both summer and fall are dry, some fish may not be able to reach their normal spawning grounds. In fall 1994, spawning in some small tributaries of the Miramichi was confined to lower reaches due to low water (Caissie, pers. obs.). The primary cause of these low flows was lack of precipitation. The extent to which anthropogenic alteration of flow patterns exacerbated the problem is unknown.

Salmon rivers are subject to intense spates in autumn in some years, but adult salmon are strong swimmers and are unlikely to be adversely affected by such events.

The hypothesis is not supported except to a limited degree in certain years.

Tests - Compare flow regimes in rivers with and without anthropogenic influences (barriers, water withdrawal, forestry operations) to determine extent of alteration of flow regimes. Document fish movements by means of fish fences, angling records, visual observations, and/or telemetry to determine effects of anthropogenic low flows on upstream movement of adult salmon. Conduct controlled experiments in which spawning participation and success of fish which are allowed to migrate upstream in summer is compared to that of fish which are held back until fall. Electrofishing in tributaries over a variety of discharge conditions would indicate whether salmon had successfully spawned the previous year.

Consequences if true - Salmon declines will continue in rivers where flow alteration and/or water withdrawal are present.

Potential for intervention - Modify water releases from water control structures to better mimic the natural annual cycles of river discharge.

I.8. Environment - thermal

I.8.a. High water temperatures delay access to spawning grounds (D. Caissie, D. Cairns)

Hypothesis - High water temperatures modify and/or delay upstream migration of adult salmon, thereby reducing the chances of their reaching good spawning habitat.

Background - Atlantic salmon are cold-water species and excessive temperatures can lead to morbidity or death. Adult salmon return to rivers in eastern North America between late spring and fall, depending on local run-timing patterns. Because salmon will not enter waters above their thermal tolerance, the presence of low water and warm zones in rivers may force spring- and summer-running fish to delay their ascent until the water cools in late summer or fall (Caissie 1995). If temperatures rise after fish have ascended the river and entered in-river pools, high temperatures may impose stress and lead to increased risk of disease.

River temperatures may be influenced by local effects (shallow impoundments which act as solar collectors, reduction of riparian shade, deforestation in the drainage area) (Brown and Krygier 1970; Cunjak et al. 1993) or international effects (global warming).

Density dependence - Density independent.

Geographic scope - Most potential effects are in the southern part of the species' range.

Probable change since 1984 - Uncertain. Long-term trends in river temperatures have not been compiled or analysed.

Evidence – Water temperature records over the past decade has shown that temperatures in many salmon rivers often approach or reach the range of lethal values for Atlantic salmon. In the case of upstream migration of adults, fish have the option of avoiding such temperatures by remaining in the estuary or lower parts of the river. Fish which have already entered the river may be trapped in high-temperature zones and in extreme circumstances die. Temperature may also heighten risk of furunculosis and other infectious diseases (see 1.3.a).

Tests - The hypothesis could be tested by comparing distribution and numbers of spawning redds in years with and without summer temperatures sufficiently high to act as thermal barriers to migration. It could also be tested by comparing densities of 0+ juveniles derived from eggs laid in warm and cool years.

Consequences if true - Salmon declines could continue as long as temperatures are high or increasing.

Potential for intervention - If hydraulic structures (e.g. ponds, dams) contribute to higher water temperatures, such effects could be reduced by modifying water release patterns. If high water temperatures are due to global warming, decrease emissions of greenhouse gases.

II. EGG TO HATCH

II.2. Aquaculture

II.2.a. Eggs from wild-aquaculture crosses have reduced viability (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - The crossing of wild and aquaculture fish produces eggs that are less viable than eggs from wild-wild spawnings.

Background - Evidence from both North America and Europe suggests that the culturing of fish over several generations leads to important genetic changes in fitness-related traits (e.g. increased growth rate, altered aggression, and reduced response to predators) (Fleming and Einum 1997, DFO 1999b), but there is no evidence of reduced egg viability. Farmed salmon produce smaller eggs (Gross 1998), and egg size is linked to viability. Most hybridization is suspected between wild males and farmed females (Fleming et al. 1997) so most hybrid eggs would be smaller with likely lower viability.

Farm origin salmon are commonly found in rivers close to areas of concentration of the salmon aquaculture industry (see I.2.a).

Interbreeding by escapees has been well documented in Europe, where negative impacts could result from genetic changes that are likely to affect the survival or competitive abilities of offspring (Gross 1998).

Density dependence - Density independent.

Geographic scope - Narrow. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and escapees only occur in significant numbers in rivers located near the industry.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada, with current annual production of 20,000 t.

Evidence - In Norway and Ireland, farmed salmon have been observed to spawn and interbreed with wild fish. In New Brunswick, cage-reared adults have successfully spawned in the Big Salmon River and have been observed spawning in the Magaguadavic River (Carr and Anderson 1997). There is no documented Canadian evidence of eggs from wild-farmed spawnings having lower viability than wild-wild spawnings. Farmed males have fewer spawnings, often do not ejaculate, and overall have less than 3% of the success of wild males in Norway.

Since most escaped farmed females would have been fed production (not broodstock) diet, egg viability may be reduced due to nutritional deficiency.

Tests - In a controlled hatchery environment, compare the survival of wild-farmed crosses at each stage of egg development with wild-wild matings. Artificial redds could be built in the wild and survival comparisons at fry emergence could be made between these same crosses.

Consequences if true - Wild populations in rivers located near the aquaculture industry will continue to decline as long as high levels of escapement persist.

Potential for intervention - See I.2.a.

II.3. Disease

II.3.a. Disease and parasitism reduce egg survival (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - Egg survival has decreased due to increases in disease and parasitism.

Background - Few pathogens, with the exception of some viruses and the opportunist *Saprolegnia* sp., are sufficiently mobile to infect spatially separated redds (Bakke and Harris 1998). Some vertically transmitted bacteria can overcome this problem by colonizing eggs during, or shortly after, laying and may cause early life stage mortality (Sauter et al. 1987). Lysosomes restrict the range of pathogens able to infect eggs, although some, for example *Renibacterium salmoninarum* (Yousif et al. 1994), and possibly *Piscirichettsia salmonis* (Larenas et al. 1996), can avoid neutralization by this defence mechanism.

Aquaculture escapees fed standard production diets (rather than specialized broodstock diets) can be expected to produce a higher proportion of infertile eggs than wild fish. These eggs would be susceptible to *Saprolegnia* sp. infestation and possibly other infections that could increase the opportunity for wild eggs to become infected.

Density dependence - Density dependent.

Geographic scope - Wide, if a change in frequency and pathogenicity of an existing pathogen or the spread of a new pathogen has occurred. Narrow, if related to aquaculture escapees, due to the localized nature of the industry.

Probable change since 1984 - Likely no change, except for possible local aquaculture industry impacts.

Evidence - There is no evidence of a major change in freshwater survival due to egg disease and parasitism. Egg-to-smolt survival has been increasing at Conne River, Newfoundland in recent years (Dempson et al. 1999a). Juvenile densities increased through the 1980s and early 1990s in the southern Gulf of St. Lawrence and juvenile abundance there is now at medium to high levels (DF0 1999a).

Tests - Fry emergence from wild redds in proximity to aquaculture redds could be compared with wild redds distant (upstream) from aquaculture redds. If artificial redds were built with control groups, it would be possible to quantify differences in pathogen levels.

Consequences if true - Continued declines unless stocks develop resistance to the pathogen(s) involved.

Potential for intervention - If a pathogen is involved, infected geographically separate areas may be quarantined to prevent the spread.

If aquaculture salmon were involved in the spread of the pathogen, improved containment would lower the risk that escaped salmon might interact unfavourably with wild stocks – see II.2.a above.

II.4. Predation

II.4.a. Predation reduces egg survival (G. Chaput and D. Cairns)

Hypothesis - Predation on eggs results in lower fry production than is assumed from adult escapement and juvenile abundance.

Background - Egg predation by salmon parr has been estimated to vary between 4% and 21% of eggs deposited in Catamaran Brook (Cunjak and Therrien 1998). Precocious male parr appear to be the most important predators. Sculpin predation on eggs may be a major factor affecting production of sockeye salmon in an Alaskan lake (Dittman et al. 1998), and schools of dolly varden trout have been reported to feed on Pacific salmon eggs (Anthony 1994). Predation by Atlantic salmon parr, brook trout and other stream fishes (cyprinids) on Atlantic salmon eggs is likely a common phenomenon.

Munro and Clemens (1937) reported that Pacific salmon eggs, including those of sockeye, chum, and coho) were a major prey item in stomachs of American mergansers collected at numerous locations in British Columbia from September to January. These authors felt that mergansers did not excavate redds to obtain eggs. Instead, they suggested that most eggs taken by mergansers had been carried by currents away from spawning sites before incorporation into the redd. On this basis they inferred that merganser predation on eggs was exerted primarily on eggs which would not have hatched even in the absence of predation (although some of the eggs in the merganser stomachs were eyed). Munro and Clemens (1937) did not indicate whether mergansers actually attended spawning events to obtain eggs as they were released. American mergansers are common in eastern Canadian salmon rivers. Salmon eggs have not been reported from merganser stomachs in this region, but this may be due to a lack of sampling effort during the egg period (Cairns 1998) or to the fact that mergansers are aggregating in areas other than spawning areas at that time of year.

Density dependence - Density dependent.

Geographic scope - Throughout the range of Atlantic salmon in North America.

Probable change since 1984 - Predation would have increased in rivers where juvenile abundance of salmon and abundance of other fish species in streams has increased. Merganser populations have not changed greatly during this period.

Evidence - Sparse evidence for egg predation. Good evidence of changes in juvenile fish abundance. There is no information on merganser predation and there has not been an increase in merganser numbers in eastern Canada (Cairns unpubl.).

Tests - Further investigate and quantify egg predation by precocious parr and other stream fishes. Measure numbers and diet of mergansers present in salmon spawning habitat during the egg period.

Consequences if true - High juvenile abundance acts as a limit to overall abundance. Optimum spawning escapements need to be defined.

Potential for intervention - Defining and managing for optimum escapement.

II.5. Life history

II.5.a, V.5.b. Reproductive output is reduced because grilse are an increasing fraction of spawners (G. Chaput)

Hypothesis - Reproductive output is reduced because of increased proportions of grilse among returns and spawners. Grilse produce fewer eggs per fish and these eggs have lower viability.

Background - Grilse (or 1SW salmon) carry fewer eggs per fish than MSW salmon since fecundity is positively associated with length and weight. Grilse also dig shallower redds than MSW salmon, because redd depth is associated with female size (Gibson 1993). There is anecdotal evidence that in hatcheries, the survival rate of grilse eggs is less than that of MSW salmon eggs (M. Hambrook, pers. comm.). The abundance of 2SW salmon in North America has declined more abruptly than the abundance of 1SW salmon (Anon. 1999a). In some rivers, grilse make up a higher proportion of the spawning runs than in previous years with the result that grilse contribute to increasing proportions of total egg depositions.

Density dependence - Density independent.

Geographic scope - Restricted to areas where 1SW salmon have important female proportions. This would include the Miramichi, PEI, the Atlantic coast of Nova Scotia, the Bay of Fundy, and Newfoundland.

Probable change since 1984 - Although 1SW fish have been increasing as a fraction of total returns, in most cases, proportion of eggs from 1SW salmon has declined because of reduced exploitation on MSW salmon.

Evidence - Only indirect evidence that 1SW salmon egg survival (as a result of shallower redds or inherent lower survival) is less than MSW salmon egg survival.

Tests - Analyze hatchery data to assess 1SW versus MSW egg viability. Assess egg to juvenile survival relative to proportion of eggs contributed by 1SW salmon as one of several potential explanatory variables.

Consequences if true - The present management strategy to limit exploitation of MSW salmon is appropriate but imposing hook-and-release angling on 1SW salmon when MSW salmon escapement is reduced will be of minimal benefit to recruitment.

Potential for intervention - Adjust fishing management regime.

II.6. Environment - chemical

II.6.a. Low pH due to acid precipitation reduces egg survival (P. Amiro)

Hypothesis - Low pH due to acid precipitation reduces egg survival.

Background - Acid precipitation results from the burning of fossil fuels and other industrial processes. Acidified emissions are transported great distances by major weather systems and have resulted in reduced water quality throughout northeast North America. Acid precipitation has reduced the pH of some drainages below the pH tolerance of many organisms (Watt 1987).

Density dependence - Density independent.

Geographic scope - Within the present range of Atlantic salmon, severe acid rain effects are limited to the geographic area called the Southern Uplands of Nova Scotia (Watt 1986). While acid deposition has decreased and alkalinity has recovered in many areas (Stoddard et al. 1999) the Southern Uplands recovery will take a much longer time (Jenkins 1999, Watt et al. 2000).

Probable change since 1984 - pH has declined since the mid 1950s and has become acutely low in some areas. At least 14 salmon rivers in the Southern Uplands of Nova Scotia have lost their ability to produce salmon due to acidification.

Evidence - Salmon have been extirpated from at least 14 rivers, severely impacted in 20 rivers and reduced in 22 rivers of the Southern Uplands of Nova Scotia (Watt 1997). The functional response between pH and egg survival is well documented and is utilized in life history process models for salmon.

Tests - Both in-situ and laboratory research has shown that all stages of Atlantic salmon including eggs are sensitive to pH's below 5.3. A pH of 4.3 is lethal to about 80% of eggs (Korman et al. 1994).

Consequences if true - Even though acid deposition has declined, heavily impacted areas will continue to be toxic to Atlantic salmon. Well buffered high pH rivers, the majority of the salmon production area, would not be affected.

Potential for intervention - A Canada - United States convention, "The Clean Air Act," was intended to reduce acid emissions and increase pH's. Data and analysis indicates that, thus far, emissions have been reduced and some recovery has taken place, but not in the Southern Uplands of Nova Scotia or in Maine. Local intervention in the form of water treatment (liming) is costly and not always economic when compared with other compensation methods and is therefore restricted to a few experimental and local applications.

II.7. Environment - physical/biological

II.7.a. Sedimentation processes reduce egg survival (D. Caissie and D. Cairns)

Hypothesis - Increased sediment deposition in salmon redds has resulted in reduced egg survival.

Background - Sedimentation in rivers can involve i) transport of suspended sediments in the water column, ii) deposition of fine sediments on the streambed, and iii) displacement of previously deposited substrate material (bedload movement).

Atlantic salmon deposit their eggs in redds. Water circulates among the gravel that forms these redds, bringing oxygen to the developing eggs and removing metabolic byproducts. Infilling by sediment reduces water movements, causing developmental delays or death to the eggs. Sediment deposition may also cover the redd, preventing hatched fry from emerging into the stream (Peterson 1978, Everest et al. 1987). In intense bedload movement events, redds can be physically displaced and the eggs within them destroyed by mechanical action.

The risk of problems due to sedimentation increases with the proportion of the substrate that is covered with fine sediment.

Density dependence - Density independent.

Geographic scope - Severe in some rivers in the southern parts of the salmon's range, where land use, particularly agriculture, is more intense.

Probable change since 1984 - More intensive land use (e.g. agricultural, forestry) may have led to an increase in the proportion of streambeds covered by fine sediments.

Evidence - High sediment levels depress or exclude salmon populations from rivers on Prince Edward Island where agricultural and other land use activity is intense (DFO 2000). Sediment has been called the leading water pollutant in the United States, and there is a great deal of literature evidence from North America and elsewhere that sediment harms reproduction of salmonid fishes (Waters 1995).

Tests - Quantification of sedimentation (e.g. fine sediments) and incubation success in rivers ranging from low and high impact by human activities.

Consequences if true – Salmon abundance will not improve in rivers where sediment impacts are important.

Potential for intervention. – Reduction and/or elimination of fine sediment pollution by modifying land use practices.

II.7.b. Alteration of discharge patterns reduces egg survival (D. Caissie and D. Cairns)

Hypothesis - Flow alteration due to dams, other artificial obstacles, water withdrawal and land use practices lowers survival of eggs.

Background - Atlantic salmon eggs are deposited in redds in the fall, incubate during the winter, and hatch in the spring. Survival until hatching requires a stable redd site which is not physically disturbed, buried by sediments, or subject to freezing temperatures (Curry et al. 1994).

Anthropogenic factors may either dampen or intensify fluctuations in flow rates (see I.7.c). If flow rates increase to flood level during egg incubation, there is a risk that the redd may be physically destroyed, infiltrated with sediment, or buried by sediment. Winter floods may also displace ice which can scour spawning beds. Studies have shown that although juveniles can be affected by such events, eggs in the gravel were not affected to the same degree (Dempson and Clarke 1999).

Winter is often a period of low flow in eastern Canadian rivers. If flow rates fall to very low levels, there is a risk that the water will freeze to the bottom, disrupting the flow of water that carries oxygen to the eggs. The eggs may also be destroyed directly if frost penetrates to the egg pockets.

Density dependence - Density independent.

Geographic scope - In general, anthropogenic effects on flow regimes are greatest in the southern, more populated part of the salmon's range.

Probable change since 1984 - Mixed (see I.7.c). Overall, there is probably little net change in the degree to which winter flow regimes in salmon rivers have been altered by human activities.

Evidence - Egg survival may be reduced by physical damage or smothering of redds, and such damage may be related to excessively low or high flows. However, there is high natural variation in flow rates and it has not been demonstrated that the flow extremes that cause damage are due to anthropogenic effects.

Tests - Compare egg survival in streams with varying flow regimes. The degree to which anthropogenic effects contribute to extreme flow events could be determined through hydrological models.

Consequences if true - Salmon declines will continue in rivers where anthropogenic flow alteration continues.

Potential for intervention. – Modify land use practices and water releases from water control structures to better reflect natural river discharge during the incubation period.

III. HATCH TO SMOLT

III.2. Aquaculture

III.2.a. Competition with aquaculture escapees reduces juvenile survival (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - Aquaculture hatchery escapees result in the presence of new size classes of fish, larger than those normally observed in wild populations. These escapees may have competitive advantages at certain life history stages and in certain environments. Also, the altered competitive balance between age classes may result in reduced wild juvenile survivorship. Predator-prey relationships could also be altered by the presence of large numbers of farmed juveniles in streams. In addition, non-maturing adult escapees entering freshwater may compete for the same food resources used by wild juveniles.

Background – Three hatcheries located within the Magaguadavic watershed are leaking farmed juveniles into the river. Escaped parr were most frequent in streams below or near commercial hatcheries (DFO 1999b). Juvenile salmon escape from aquaculture hatcheries due to accidents, inadequate containment, and sometimes intentional release.

Density dependence - Density dependent.

Geographic scope - Narrow. The aquaculture industry is concentrated in small areas of the Northwest Atlantic, and escapees only occur in significant numbers in rivers on which hatcheries for the industry are situated.

Probable change since 1984 - Increase. Farmed salmon production has increased greatly in eastern Canada, with current annual production of 20,000 t. Private hatcheries have increased in number and production levels (DFO 1999b).

Evidence – Introduced fish alter the natural stream environment of wild salmon by elevating densities and increasing overall levels of competition, in some cases to the disadvantage of indigenous fish (Einum and Fleming 1997). Introductions can also lead to predator attraction, by raising local fish densities or because of aberrant forms of behaviour (Youngson and Verspoor 1998).

Escaped farmed juvenile salmon have been reported from four New Brunswick rivers, the Digdeguash, Magaguadavic, Waweig, and Nashwaak. Escapees from hatcheries are commonly larger than wild salmon of the same age, which can be an important advantage in competitive contests (DFO 1999b).

The high natality of fishes, coupled with a seasonal environment where space and invertebrate drift resources decline drastically each year in many systems, ensures that resources will be limited, resulting in high intraspecific competition (Grant et al. 1998). After a few generations in the high density niche of aquaculture, farmed juveniles aggressively out-compete wild juveniles in competition experiments and hybrids show intermediate aggression levels (Einum and Flemming 1997). Fergusen et al. (1997) placed three lines of fish – farmed, wild, and hybrid – into an Irish river to study their behavior and growth. The farmed fish behaviorally displaced the wild fish into downriver sections where feeding rates are probably lower; the farmed fish grew fastest, the hybrids intermediate, and the wild fish slowest.

Tests - Competition has been clearly demonstrated by the evidence above. Further experimentation is needed to clearly confirm that wild juvenile survivorship has been reduced.

Consequences if true - Wild populations in rivers with aquaculture hatcheries will be negatively affected as long as hatcheries continue to leak juveniles into the river.

Potential for intervention - See I.2.a.

III.3. Disease

III.3.a. Disease and parasitism reduce juvenile survivorship (T. Goff, D. Sutherland, and S. Ratelle)

Hypothesis - New diseases or parasites have reduced juvenile survivorship.

Background - In Europe during the 1990s, the primary ecological impact of cultured Atlantic salmon on wild fish health is through the transfer of diseases and parasites (Bakke and Harris 1998, Gross 1998). For example, *Gyrodactylis salaris* was carried by farmed Swedish smolts out of the Baltic Sea drainage and into the eastern Atlantic drainage, where it is known to have extirpated over 35 wild populations in Norway (Johnsen and Jensen 1991). The transfer may have occurred during enhancement projects. *Aeromonas salmonicida* or furunculosis was carried by Scottish smolts to Norwegian aquaculture and probably spread through escapees to infect hundreds of wild populations (Johnsen and Jensen 1994). It was recently found in Scotland that sea lice are denser on 1 sea-winter escaped farmed fish than 1 sea-winter wild fish (Jacobson and Gaard 1997). These parasites may contribute to increased stock mortality, reduced marine growth, and premature return of adults (Todd et al. 1997). While new diseases and parasites will surely appear, the current problems are now better controlled in the aquaculture niche, except perhaps for sea lice and recent outbreaks of infectious salmon anemia (ISA) (Gross 1998). Disease/parasites can also be introduced through unregulated and careless transfers of fish and equipment by private interests and anglers among watersheds.

Density dependence - Density dependent .

Geographic scope - Wide. If a new disease or parasite is causing problems in freshwater, it could be spread widely with an appropriate vector (birds, sea lice, human transfer of fish, etc.).

Probable change since 1984 - Likely the same, unless related to the growing aquaculture industry. Historically, anglers have been responsible for introductions of exotic fish species within the Maritimes (ex. smallmouth bass, chain pickerel, brown bullhead).

Evidence - In the Maritimes, there are limited data on disease prevalence and trends. Farmed and wild finfish populations have not been thoroughly assessed. There is no evidence that, in the Maritimes Region, diseases of farmed fish have had an impact on wild fish or vice versa (DFO 1999b). No new diseases or parasites of juveniles have been reported. There is no evidence of a major change in freshwater survival due to new diseases.

Tests - Develop improved sampling of both wild and aquaculture populations so that existence of and trends in disease prevalence can be analyzed. Examine historical inter-stage juvenile survivals for evidence of decreased survival in freshwater.

Consequences if true - Salmon abundance will not increase until wild stocks develop resistance to problem diseases.

Potential for intervention - Negative effects can be reduced by producing healthy farmed salmon. Various initiatives under development to reduce potential fish health problems on fish farms include: preparation of codes of practice by the industry, provincial initiatives to develop and implement fish health programs, and at the federal level, the revision of the Fish Health Protection Regulations. Various additional requirements to strengthen existing fish health programs include: adequate compensation in cases where fish have to be destroyed due to an exotic disease, development of more sensitive diagnostic tools, disease surveillance of wild stocks, and mandatory reporting of exotic diseases. It is recognized that the lack of approved therapeutants restricts the ability of farmers to manage the impact of diseases.

Educate the public on the risks of disease and parasite introductions by unauthorized transfer of fish between watersheds.

III.4. Predation

III.4.a. Avian predators reduce juvenile survival (D. Cairns)

Hypothesis - Predation by birds, particularly common mergansers and belted kingfishers, decreases survival of juvenile salmon.

Background - Common mergansers and belted kingfishers are major avian predators of juvenile Atlantic salmon (Cairns 1998). Kingfishers tend to take juvenile salmon of the smaller size ranges, while mergansers can take juvenile salmon of any size.

Density dependence - Both density dependent and density independent. Predation may occur at low prey levels if predators are attracted to the area by other prey. Predation rates may increase if juvenile salmon densities are high, leading to greater attraction of predators.

Geographic scope - Bird predation may occur throughout the freshwater range of Atlantic salmon.

Probable change since 1984 - There is no evidence of increases of major avian predators of salmon in freshwater.

Evidence - Bioenergetic models have estimated that common mergansers and belted kingfishers harvest from 21% to 45% of juvenile salmon in Maritime rivers in each juvenile year (age 0+ to 2+) (Cairns unpubl.). However, analysis completed to date of historical culling experiments provides no evidence that a reduction in merganser and kingfisher numbers leads to increased juvenile salmon populations (Anon. 1996). Mortality due to mergansers and kingfishers therefore appears to be compensatory rather than additive. There is no evidence of an increase in merganser or kingfisher numbers coincident with the decline in salmon returns. Juvenile densities in major Maritime rivers have remained high during the period of declining returns.

Tests - Further analysis of historic studies of predator culling in Maritime rivers could confirm or refute the preliminary conclusion that predator culls do not increase salmon populations.

Consequences if true - Salmon abundance will not increase unless predator numbers fall.

Potential for intervention - Predation pressure could be reduced by predator culls or increased predator harvests. Such programs would encounter strong opposition.

III.5. Life history

III.5.a. Precocious maturation reduces the number of juveniles which will become adults (P. Amiro)

Hypothesis - Precocious maturation reduces the number of juveniles that will smoltify, go to sea, and return as adults.

Background – Atlantic salmon commonly exhibit a life history variation in which juvenile males become sexually mature. Parr with precocious maturation have been noted throughout the range of Atlantic salmon (Myers et al. 1986).

Density dependence - Unknown.

Geographic scope - Throughout the range.

Probable change since 1984 - Unknown.

Evidence - While higher winter mortality of precocious parr is suspected (Power 1969, Dalley et al. 1983), fully re-conditioned previously precocious smolts have also been observed. The survival of precocious parr, which affects the number of smolts produced, may be dependent on latitude of the river. Precocity rates are dependent on growth rate and photoperiod (Thorpe 1994). Growth rate of parr is dependent on density (Bohlin et al. 1994). Whether precocity of parr can be significantly altered by parr density without a coincident increase in photoperiod or an increase in productivity, is unknown. The temporal trend in precocity rate or survival of precocious parr is untested and unknown.

Tests - Scale samples and carcasses, together with gender identity, collected from wild smolts and adults could provide analytical data. Also, change in gender ratios between smolts and returning adults may provide an alternate test of the hypothesis. There are limited locations where these data are available.

Consequences if true - The proportion of females in returning salmon may increase. The probability of unfertilized eggs would remain similar given the documentation of successful salmon x precocious parr spawning. Therefore while the numbers of returning salmon may decline the production of smolts would remain relatively unchanged.

Potential for intervention - No known intervention measures.

III.5.b. Inter- and intra-specific competition reduces juvenile survival (G. Chaput)

Hypothesis - Density-dependent factors limit carrying capacity thus limiting juvenile production.

Background - Atlantic salmon juveniles are territorial and competitive (Gibson 1993). Year-class abundance declines over time as a result of competition for limited resources (Grant 1993). Inter-stage survival rates decline with increasing egg deposition with the result that the relationship between egg deposition and juvenile abundance is curvilinear and can be modeled by asymptotic or over-compensatory functions (Hilborn and Walters 1992). Biological reference points which define spawning escapement objectives are based on the compensatory association between spawning abundance and recruitment.

Density dependence - Density dependent.

Geographic scope - Potentially universal, but less likely to occur where juvenile densities are low or are well below carrying capacity.

Probable change since 1984 - Juvenile abundance is at record high levels in some areas of eastern Canada. Egg depositions in some rivers are at or well above the conservation requirement. In other areas where escapements and juvenile abundance have declined, density-dependent factors should be less important in constraining inter-stage survival.

Evidence - A large body of literature supports density-dependent factors determining abundance (Elson 1975, Elliott 1993, Chaput et al. 1998a). The conservation requirement for Atlantic salmon in eastern Canada was derived on that premise.

Tests - Numerous data sets have been analysed demonstrating this phenomenon.

Consequences if true - Escapements at or above conservation levels will not produce any important increases in recruitment. In rivers where the conservation requirements are too high, recruitment will be below expectation and may be more variable than at lower escapement levels.

Potential for intervention - Optimum spawning requirements need to be tailored to the carrying capacity of individual rivers. Revisions to presently used default conservation requirement should be undertaken using the set of index rivers in eastern Canada.

III.6. Environment - chemical

III.6.a. Toxic chemicals reduce juvenile survival (G. Chaput).

Hypothesis - Juvenile abundance is reduced by chemical pollution.

Background - Many Atlantic salmon rivers are located in watersheds containing industrial, mining, forestry, and agricultural operations. Such operations may release chemicals which acutely impact the aquatic environment. Documented cases of impacts include effects of DDT spraying in New Brunswick forests (Elson 1967), base metal mining in the Miramichi River (Elson 1974, Zitko 1995) and Nepisiguit River and fish kills associated with agricultural pesticide run-off (DFO 2000).

Density dependence - Density independent.

Geographic scope - May occur throughout the salmon's range, but generally more severe in southern regions.

Probable change since 1984 - Impacts from forestry spraying are probably reduced. Mining impacts are likely also reduced but not eliminated. Continued/increased impact from agricultural practices in some areas.

Evidence - Juvenile surveys indicate reduced to no impact from these activities with the exception of industrial accidents. On Prince Edward Island, there were eight fish kills in agricultural watersheds in summer 1999, including one which eliminated fish from much of the Valleyfield River, one of the province's major (by PEI standards) salmon rivers.

Tests - Juvenile abundance relative to escapements would indicate areas of concern.

Consequences if true - Salmon populations will decrease in rivers which are subject to chemical pollution.

Potential for intervention - Legislation exists to prevent these impacts but enforcement is frequently insufficient.

III.6.b. Low pH due to acid precipitation reduces juvenile survival (P. Amiro)

Hypothesis - Low pH due to acid precipitation reduces juvenile survival.

Background - See II.6.a

Density dependence - Density independent .

Geographic scope - See II.6.a.

Probable change since 1984 - See II.6.a.

Evidence - Both in-situ and laboratory research has shown that all stages of Atlantic salmon are sensitive to pH's below 5.3 (Korman et al. 1994). Alevin are sensitive to pH less than 5.5 and 80% mortality can be expected at pH 4.3. Fry are sensitive to pH less than 6.5 and 80% mortality can be expected at pH 4.7. Smolts are sensitive to pH less than 5.3 and 80% mortality, some times delayed, can be expected at pH 4.3.

Tests - Both laboratory and in-situ experiments have been conducted.

Consequences if true - See II.6.a.

Potential for intervention - See II.6.a.

III.7. Environment - physical/biological

III.7.a. Sedimentation processes reduce juvenile survival (D. Caissie and D. Cairns)

Hypothesis – Increased suspended sediment and sediment deposition reduces juvenile survival. In particular, infilling of under-boulder habitat reduces survival of pre-smolts.

Background - See also II.7.a. Sedimentation has profound effects on stream ecology (Waters 1995). Many stream invertebrates require rocky substrates which offer firm surfaces to attach to and cavities in which to hide. When such substrates are covered by sediments, invertebrate populations are reduced, which reduces the food supply for stream fishes including juvenile salmon.

Juvenile salmon also require interstitial spaces for cover. As juvenile salmon increase in size, larger interstitial spaces are needed. Such cover is particularly important in winter when fish activity is reduced. Sediment may fill spaces between gravel, cobble, and boulders in the stream bed, thereby denying appropriate habitat to juvenile salmon.

Fish tend to avoid streams with continuing high suspended sediment loads, although high concentrations can be tolerated for short periods of time.

Ice break-up can be classified as thermal break-up, in which the ice melts with little potential for jamming, and dynamic break-up, in which the ice is broken by the force of water. Dynamic break-ups are often accompanied by ice jams (Prowse 1993). Dynamic break-ups have been shown to double sediment concentrations, and dynamic break-ups may increase sediment concentrations by a factor of six. Large bedload movements may occur during ice break-up due to ice scouring and flood events (Scrimgeour et al. 1994).

Density dependence - Density independent.

Geographic scope - Generally more severe in the southern part of the salmon's range, where more intense land use leads to greater movement of soil from land to rivers.

Probable change since 1984 - Land use practices that increase sediment pollution have increased in Prince Edward Island. Elsewhere, there has been widespread forest harvest within the drainage areas of salmon rivers, but improved harvest practices (stream-side buffer zones etc.) in some areas may have reduced sediment transfer to streams.

Evidence - Sediment deposition has been associated with poor salmonid production in numerous studies (Waters 1995, DFO 2000).

Tests - Quantification of sedimentation (e.g. fine sediments) and juvenile survival, including survival to the smolt stage, in rivers ranging from low and high impact by human activities.

Consequences if true - Salmon abundance will decrease in rivers where sediment impacts are increasing.

Potential for intervention - Reduction of sediment pollution by modifying current land use practices. Enforce current laws regarding release of harmful substances into fish habitat.

III.7.b. Alterations to discharge patterns reduce juvenile survival (D. Caissie and D. Cairns)

Hypothesis - Flow alteration due to dams, other artificial obstacles, water withdrawal and land use practices lowers survival of juveniles.

Background - In general, moderate flow regimes are favourable to the survival of juvenile salmon, and flow regimes characterized by extreme events are harmful (Elwood and Waters 1969, Erman et al. 1988). Low flow conditions reduce water depth and stream width, decreasing available habitat. Low flow conditions also make the water more susceptible to excessive heating. In winter, low flow conditions may allow the water to freeze to the bottom, forcing wintering fish out of preferred habitat into alternate habitats where mortality risks may be higher (Frenette et al. 1984, Chadwick 1982).

High flow conditions may lead to reduced visibility due to higher suspended sediments and lack of low velocity refuge sites. Flood conditions may wash fish down river and in extreme conditions (Dempson and Clarke 1999), may cause extensive mortality to salmonid populations due to large-scale bedload movement (Jowett and Richardson 1989).

Ice movements can disrupt physical habitat and trap or even crush fish. Ice jams may form during ice break-up, which can lead to floods with attendant danger to fish.

Density dependence - Density independent.

Geographic scope - In general, anthropogenic effects on flow regimes are greatest in the southern, more populated part of the salmon's range.

Probable change since 1984 - Mixed (see I.7.c). Overall, there is probably little net change in the degree to which winter flow regimes in salmon rivers have been altered by human activities.

Evidence - In a small tributary of the Miramichi River, winter floods associated with ice cover appear to reduce juvenile salmon survival. Data from Quebec and Newfoundland suggest that poor juvenile salmon survival is associated with late winter low flows. Flow regimes are naturally variable, and it has not been demonstrated that the low flow conditions noted above are due to human activities.

Tests - The relation between extreme hydrological events and juvenile survival could be further examined by comparing juvenile survivorship across rivers and across years with varying hydrological regimes. Further field studies could be undertaken to clarify the means by which hydrological events impose mortality. Hydrological modelling could be used to determine whether extreme events have an anthropogenic cause.

Consequences if true - Salmon declines could continue or recover depending on the presence of extreme discharge events in the future.

Potential for intervention. – If hydrological events are of natural origin, intervention becomes very difficult. However, if hydrological changes are due to anthropogenic perturbations then mitigation could be achieved by removing dams or changing their intake patterns, or by changing land use practices to reduce surface run-off.

III.8. Environment - thermal

III.8.a. High summer temperatures reduce juvenile survival (D. Caissie and D. Cairns)

Hypothesis - High summer water temperatures limit production of juvenile Atlantic salmon directly by temperature-induced mortality, or indirectly by reducing available habitat or increasing risk of predation or disease.

Background - Atlantic salmon prefer cool water. Temperatures above 29°C have been shown to cause death in juvenile Atlantic salmon (Grande and Andersen 1991, Elliott 1991). Warmer river temperatures have also been monitored in Newfoundland in recent years (Dempson et al. 2001). In the Miramichi River, juvenile salmon have been found to move to cooler tributaries when temperatures reach the mid-20s (Cunjak et al. 1993). However, in the Midgell River, PEI, juvenile Atlantic salmon remained in the main river when temperatures were in the high 20s, despite the availability of thermal refugia which were cooled by spring seepages (MacMillan 1998).

Fish which change habitats to avoid high temperatures may be subject to crowding which lowers feeding opportunities and increases risk of predation and disease. In the Midgell system noted above, brook trout moved into spring-fed refugia when the river warmed to the low 20s. Total trout population of the Midgell was approximately one tenth that of the nearby Valleyfield River, which is similar in size but which remains cool in the summer.

Density dependence - Density independent.

Geographic scope - There are widespread reports of excessive temperatures in salmon rivers in eastern North American. However the extent of the problem is unclear because temperature records have not been systematically compiled. The problem is most likely to occur in the southern part of the salmon's range.

Probable change since 1984 - Uncertain.

Evidence - There are numerous reports of water temperatures in many river systems that approach or reach the range of lethal values for Atlantic salmon during at least some summers. There is a body of literature which demonstrates that temperature regimes control the geographic distribution of salmonids in freshwater.

However, it has not been determined whether river temperatures are increasing within the salmon's range.

Tests - The hypothesis can be tested by compiling available river temperature records, and determining the portion of habitat which faces temperature problems. River temperatures are closely linked to precipitation and atmospheric temperatures, for which the data record is much longer. Therefore river temperatures can be estimated with reasonable confidence for the time period dating back to the beginning of reliable weather records. This method permits the generation of long-term time series of river temperatures.

Consequences if true - Salmon abundance will decline if temperature rises continue.

Potential for intervention - If hydraulic structures (e.g. ponds, dams) contribute to higher water temperatures, such effects could be reduced by modifying water release patterns. If high water temperatures are due to global warming, decrease emissions of greenhouse gases.

III.8.b. Limited availability of thermal refugia reduces juvenile survival (D. Caissie and D. Cairns)

Hypothesis - Changes in hydrologic regimes due to human activities have reduced availability of cool-water refugia which juvenile salmon need to avoid lethal summer temperatures.

Background - Juvenile Atlantic salmon may enter cool water refugia when water temperatures in their normal habitat surpass their tolerance limit (Cunjak et al. 1993, Beschta et al. 1987). Thermal refugia are commonly either areas of water with seepages of cool groundwater, or tributaries with lower temperatures than the main river.

Atlantic salmon have been observed to shift to thermal refugia in the Miramichi River when the temperature in their normal habitat reached the mid 20s (Cunjak et al. 1993). In the Midgell River, PEI, juvenile salmon did not move to thermal refugia even when the temperature reached the high 20s (MacMillan 1998).

Density dependence - Density dependent or independent. Thermal refugia are often small and therefore have limited capacity to accommodate fish. Temperature can exert stress or mortality on fish directly, but indirect effects (disease transmission, increased predation risk) depend on fish density.

Geographic scope - Uncertain, because the need for and the availability of thermal refugia has not been systematically examined. The requirement for thermal refugia is likely to be more common in the southern part of the salmon's range.

Probable change since 1984 - Uncertain.

Evidence - The extent to which thermal refugia are necessary to avoid temperature-induced mortality is uncertain due to the conflicting observations in the Miramichi and Midgell Rivers. In the latter river, juvenile Atlantic salmon were seen swimming in the main river channel when temperatures were about 29°C, despite the availability of nearby thermal refugia.

Thermal refugia in groundwater springs depend on continued groundwater supplies. For thermal refugia in tributaries, cool water depends on a variety of factors including groundwater seepage, forest cover and shade, and water residence time. Trends in availability of thermal refugia in rivers, and in the factors which influence them, have not been systematically compiled or analysed for Atlantic salmon rivers.

In general, a warming trend in regional climate will increase the need for and decrease the availability of thermal refugia.

Tests - To test this hypothesis further data are required on the thermal tolerance of wild juvenile Atlantic salmon, the present extent of use of thermal refugia, and trends in the availability of thermal refugia.

Consequences if true - If the hypothesis is true, salmon declines could continue as a result of potential global warming.

Potential for intervention - If hydraulic structures (e.g. ponds, dams) contribute to higher water temperatures, such effects could be reduced by modifying water release patterns. If high water temperatures are due to global warming, decrease emissions of greenhouse gases. The carrying capacity of present thermal refugia could be enhanced by excavation of stream seepages or provision of cover that protects small fish from larger fish and other predators.

III.8.c. Climate change will lead to excessive river temperatures that will depress juvenile production (D. Cairns)

Prediction - Global climate change will cause temperatures in some rivers to exceed the thermal tolerance of salmon, leading to loss of habitat and depressed production.

Background - The main scientific authority in the field of global climate change is the Intergovernmental Panel on Climate Change (IPCC), which was set up by the United Nations Environmental Program and the World Meteorological Organization. Climate change projections are based on global circulation models (GCMs) in which atmospheric and ocean dynamics are modeled on a global 3-dimensional grid, on the basis of various scenarios of greenhouse gas emissions (IPCC 1995a, b). Because GCMs require huge amounts of processing power, they are set up with coarse geographic resolution, typically 250 km in horizontal dimensions and 1 km in the vertical dimension.

Climate change models can be designed to run on a regional level with a higher resolution. No regional climate change model is currently available for eastern Canada (K. Drinkwater, Department of Fisheries and Oceans, pers. comm.).

The following highlights of the climate change issue are primarily from IPCC 1995a.

Global mean surface air temperature has increased by about 0.3 to 0.6°C since the late 1800s. Temperatures in North America have increased from 1 to 2°C, with most of the increase occurring at night. There is much regional unevenness in the pattern of change. Some areas have shown cooling tendencies, including the northern North Atlantic ocean.

Given the mid-range of greenhouse gas scenarios, the models project a mean global increase in surface air temperature of 2°C between 1990 to 2100. Projections under the range of modeled scenarios vary from +0.9 to +3.5°C.

In general, sea surface temperatures increase with air temperature, but not as rapidly or as much. Hence worldwide rises in SST are expected. However, the temperature of water in the North Atlantic depends on the strength of the Great Conveyor Belt system, which circulates water between the Atlantic and Pacific Oceans via the Indian Ocean. This system weakens when temperatures increase. Consequently some models show a decrease or only a marginal increase of sea surface temperatures in the northern North Atlantic in response to increasing greenhouse gases.

Stream water temperature increases at a rate of 0.9 x the increase in air temperature (IPCC 1995b). Groundwater temperature is approximately mean annual air temperature + 1° to 2°C (Meisner 1990b). Hence increases in freshwater temperatures are expected.

In mid-latitude terrestrial regions, a 1°C temperature increase is equivalent to a poleward shift of 150 km in temperature isotherms (IPCC 1998). Hence modeled increases of 1 to 3.5°C would move isotherms north by 150-550 km. This rule of thumb does not apply to marine environments.

Data are inadequate to determine if climate variability or weather extremes have increased. The models predict that weather extremes, including extreme temperature events, may be more frequent in some regions but less frequent in others. A more vigorous hydrological cycle is expected with prospects for more severe droughts and floods in some places and less severe droughts/floods in other places (IPCC 1995a). Model simulations provide some suggestion of more extreme rainfall events.

Ice mass in mountain glaciers is expected to decrease by 1/3 to 1/2 under climate change, and sea ice in the Arctic is expected to substantially diminish. However, little change is expected in the extent of the Greenland and Antarctic ice sheets in the next 50-100 years (IPCC 1995b).

The patterns of ice jams in rivers is expected to increase in some areas and decrease in others.

In addition to IPCC reports, there is a large body of literature on climate change effects on fish (Frank et al. 1990, Meisner 1990a, Mangel 1994, Beamish 1995, Drinkwater 1997, Rouse et al. 1997, Wood and McDonald 1997). Some of the main findings follow.

A generalized poleward shift of species distributions is expected in both freshwater and marine environments. In fresh water, southern limits are set by upper lethal temperatures (Moore et al. 1997). Detailed analyses of expected changes in southern limits of salmonids have been generated for some areas in central North America (Minns and Moore 1995, Stefan et al. 1995), but no such analysis has been conducted for Atlantic Canada.

Diversity of freshwater fish fauna is expected to rise because warm water supports more species than cold water, but such increases may be constrained if fish cannot reach newly suitable areas due to lack of connecting habitat (Minns and Moore 1995).

Fish growth is expected to increase. Mean age of salmon smoltification may decrease from 8 to 29% (Minns et al. 1995). Changes in river discharge will produce changes in amount of fluvial habitat. Effects will vary regionally. Overall change in eastern Canada is projected to be -4% (Minns et al. 1995).

Juvenile salmon prefer cool water, and temperatures above the mid-to-high 20s may cause stress or death. Growth increases and smolt age decreases with temperature, provided that optimal temperatures are not exceeded (Power and Power 1994).

Density dependence - Density independent.

Geographic scope - Effects will be greatest in the southern part of the range. Temperature isotherms will shift northward approximately 150 km for each degree of air temperature increase (IPCC 1998).

Evidence - Warmer water due to projected climate change will enhance growth rates and decrease mean smolt ages. However, climate change may also make some areas unsuitable for salmon production due to excessive summer temperatures. The extent to which this might occur has not been systematically examined. Climate models predict that weather will become more extreme in some areas. If this occurs in the freshwater range of Atlantic salmon, extreme water temperatures caused by droughts and hot periods could eliminate salmon from some areas, even if mean temperatures rise only modestly.

Tests - Habitat loss due to excessive summer temperatures could be examined by adding projected temperature increases to available data on stream temperatures. A full assessment of potential habitat loss from this cause would require detailed assessment of the availability of thermal refugia for salmonids, and the extent to which such refugia can protect against mortality.

Consequences if true - Salmon populations will decrease at the southern end of the range and may increase at the northern end.

Potential for intervention - Peak summer temperatures can be moderated to some degree through land-use practices that allow riparian shading and forest cover in watersheds. It may be possible to enhance the effectiveness of thermal refugia by such measures as excavation of stream seepages and provision of cover that protects small fish from larger fish and other predators.

IV. SMOLT MIGRATION THROUGH RIVERS AND ESTUARIES

IV.2. Aquaculture

IV.2.a. Aquaculture escapees increase competition for resources in the estuary (J. Ritter)

Hypothesis - Aquaculture escapees compete with wild salmon for food resources in the estuary and thereby decrease smolt-to-recruit survival.

Background - Potential for competition exists from escapees from both freshwater hatcheries and marine cages.

Density dependence - Density dependent; the greater the density of wild salmon, or abundance of escapees, the greater the potential for competition for food resources.

Geographic scope - Localized to the rivers on which hatcheries are located or to river estuaries in close proximity to marine grow-out sites.

Probable change since 1984 - The abundance of escapees has increased with the dramatic growth of the aquaculture industry during the late 1980s and through the 1990s (DFO 1999b).

Evidence - No direct evidence.

Consequence if true - Smolt-to-recruit survival would be reduced.

Potential for intervention - Improved containment of salmon in hatcheries is feasible with implementation of compliance monitoring. Better containment in marine cages is also feasible but complete containment never will be achieved.

IV.4. Predation

IV.4.a. Bird and seal predation reduces survival of smolts in rivers and estuaries (D. Cairns)

Hypothesis - Bird and/or seal predation reduces survival of smolts descending rivers and passing through estuaries.

Background - Smolts leaving rivers must pass through estuaries on their way to the sea. The main endothermic piscivores in estuaries are cormorants, gulls, and seals. Smolts encounter this predation field at a time when they are under osmotic stress due to their entry into brackish and salt water (Handeland et al. 1996).

Density dependence - Density independent. Because the smolt run occurs during a relatively short period of time and because smolts are a relatively small portion of the biomass of estuarine finfish, predation probably acts in an additive rather than compensatory way. Smolt runs could possibly increase the predation rate by attracting predators, but they could also reduce it by swamping them. In the Maritime provinces and New England, predator attraction is more likely controlled by runs of abundant non-salmonid fishes such as smelts and gaspereau, whose biomasses are typically much greater than those of smolts (Chaput 1995).

Geographic scope - Wide. Potential bird and seal predators occur in estuaries of salmon rivers throughout the species' range.

Probable change since 1984 - Gull use of estuaries in Newfoundland appears to have increased in the 1990s following the collapse of the groundfishery, which provided feeding opportunities for gulls (W.A. Montevecchi, Memorial University of Newfoundland, unpubl. data). Cormorant numbers have increased in eastern Quebec and the Maritimes in the past 30 years but changes since 1984 are irregular (Chapdelaine and Bédard 1995, Milton et al. 1995). Seal numbers have increased throughout the North American range of Atlantic salmon (Hammill and Stenson 1997). According to commercial fishers contacted through mail-out and phone surveys in Labrador and Prince Edward Island, seal numbers have increased in estuarine and inshore waters (Reddin and Felt 1998, Cairns et al. 2000). Elsewhere, anecdotal reports from fishers and fisheries officers suggest that seals are more numerous in estuaries and inshore waters, but no quantitative surveys are available.

Evidence - In Maine, double-crested cormorants are estimated to remove 7% of descending hatchery-reared smolts (Blackwell 1996). Most predation occurs at dams which delay and concentrate smolts. In the Maritime provinces, cormorant diets have never been measured in or near major salmon rivers. However, bioenergetic modeling shows that cormorants could remove a substantial percentage of smolts passing through estuaries of some salmon rivers, even if salmon are a small fraction of cormorant diet (Cairns unpubl.). Substantial numbers of gulls visit estuaries of salmon rivers in Newfoundland during smolt runs, and seals are present in estuaries of many salmon rivers throughout the species' range. However, diet of gulls and seals during smolt runs has not been measured.

Other than the case of cormorants preying on descending smolts in Maine, data are insufficient to confirm or refute this hypothesis.

Tests - The hypothesis could be tested by detailed studies in test estuaries, involving i) estimation of the size of the smolt run, ii) counts of potential smolt predators during the smolt run, iii) diet investigations of potential predators using large sample sizes, and iv) estimation of predator consumption of salmon and salmon exploitation rates.

Consequences if true - Salmon returns will continue to decline if predator numbers remain the same or increase.

Potential for intervention - Predation pressure could be reduced by predator culls or increased predator harvests. However, such programs would encounter strong opposition.

IV.4.b Fish predation reduces the survival of smolts in rivers and estuaries (E. Baum and D. Cairns)

Hypothesis - Predatory fish in lower rivers and in estuaries have increased, resulting in higher predation mortality on out-going smolts.

Background - Potential fish predators of exiting smolts include wide variety of riverine, estuarine and marine species including burbot, pike, pickerel, sea trout, eels, cod, and other groundfish (Anthony 1994). Striped bass are also predators (Blackwell and Juanes 1998).

Density dependence - Density dependent, if predatory fish aggregate to take advantage of smolt runs.

Geographic scope - Groundfish may be present in estuaries in the entire range of Atlantic salmon in North America. Large predatory freshwater fish (pike, pickerel) are generally more abundant in the southern part of the salmon's range.

Probable change since 1984 - There have been major changes in marine fish assemblages in the northwest Atlantic since 1984. Groundfish have decreased greatly and there have been increases in cartilaginous fish. These changes in overall marine fish composition are presumably reflected in fish faunas that use lower estuaries. Populations of striped bass have shown a major increase the northeastern US (Shepherd 1999), but numbers are generally depressed in the Maritime Provinces (Bradford et al. 1999).

Evidence - Atlantic salmon were found be significant prey of striped bass at the Essex Dam on the Merrimack River, Massachusetts, in 1997 but not in 1998 (MacNeil and Juanes 1999).

Tests - Examine data sets including groundfish surveys for information on presence and abundance of potential smolt predators in rivers and estuaries. Where abundance of potential predators has changed, compare such changes with changes in marine survival or returns of salmon to local rivers. Investigate diets of potential fish predators and estimate numbers of smolts eaten.

Consequences if true - Sea survival will remain low as long as fish predation on smolts is high.

Potential for intervention - Reduce numbers of predatory fish through commercial or recreational fishing or through culls.

IV.4.c Aquaculture sites attract predators, thereby increasing predation on out-going smolts (D. Cairns and D. Meerburg).

Hypothesis - Predators, especially seals, are attracted to aquaculture sites. Smolts that pass through this predation field suffer increased predation mortality.

Background - Salmon confined to sea cages offer a concentrated food supply which may attract predators, including seals (Morris 1996), seabirds, fish, and anglers to aquaculture sites. Birds and seals could be repelled from aquaculture areas by harassment and shooting, although such techniques often seem to have little long-term effect on predator behaviour. At times large numbers of salmon escape from cages, which could potentially condition predators to favour salmon as prey.

Density dependence - Density independent.

Geographic scope - Coastal areas where sea-cages are located.

Probable change since 1984 - Possible increase with expansion of salmon aquaculture industry,

Evidence - The number of seals in the vicinity of aquaculture sites is unknown, but the continuing occurrence of salmon escapes due to seal-induced gear damage indicates that seals continue to visit aquaculture sites. Like sea-cages, herring weirs represent a concentrated source of potential prey for seals. However, Colbourne and Terhune (1991) were unable to detect any association between harbour seal movements and the appearance of herring at weir sites. Fall surveys of seal distribution in the Bay of Fundy showed no evidence that seals are attracted to aquaculture sites (Jacobs and Terhune 2000).

Tests - Count seals, seabirds and anglers near aquaculture sites and compare to counts at distant control sites. Compare fish densities close to and distant from aquaculture sites. Experimentally release aquaculture salmon and monitor seal behaviour. Radio-tag seals and monitor behaviour before and after a release of salmon.

Consequences if true - Sea survivorship of salmon whose natal rivers exit near aquaculture sites will continue to be low.

Potential for intervention - Reducing the vulnerability of sea-cages to seal attacks will reduce their attractiveness to seals and seabirds. Eliminate predators which visit aquaculture areas.

IV.5. Life history

IV.5.a, V.5.a. Density-dependent effects in freshwater affect subsequent survival at sea (G. Chaput)

Hypothesis - Density-dependent factors impinging on juvenile salmon in freshwater affect subsequent survival at sea.

Background - There is evidence that survival of smolts at sea is size-dependent (see summary in Hansen and Quinn 1998). But other factors such as time of entry into the ocean (Dempson et al. 1998), which also appears to have a size-dependent function (larger smolts leave first) are associated with variations in sea survival (Hansen and Quinn 1998). Body size could be important for several reasons: osmoregulatory ability, swimming ability affecting predator avoidance, or range of available prey sizes. Studies have shown that mean smolt length at age decreases as juvenile density in fresh water increases (Gardiner and Shackley 1991, Korman et al. 1994, Orciari et al. 1994).

Density dependence - Density dependent.

Geographic scope - Of concern for those rivers (areas) where juvenile abundance has increased in the last decade (southern Gulf).

Probable change since 1984 - Juvenile abundance is at record high levels in some areas of eastern Canada. There have not been any continuous smolt and juvenile sampling programs in the same river.

Evidence - Documented in literature, although sparsely.

Tests - Analyse juvenile data sets for associations between size-at-age of parr and density, analyse historical data sets with smolt and juvenile sampling (for example Miramichi 1960s through early 1980s), analyse from scales, back-calculated smolt size of returning adults.

Consequences if true - Resource management objectives based on maximizing the abundance of juveniles in the river may result in less than maximum recruitment of adults.

Potential for intervention - Optimum spawning requirements need to be defined for individual rivers. Revisions to presently used uniform conservation requirement within the Maritimes should be undertaken using the set of index rivers in eastern Canada.

IV.6. Environment - chemical

IV.6.a. Toxic chemicals affect smolt migration and reduce survival (G. Chaput)

Hypothesis - Smolts migrating through estuaries are negatively impacted by pollution and chemicals.

Background - Major industries requiring water for intakes and effluent discharge are frequently located in the lower parts of rivers and estuaries. Pollution from pulp and paper mills, oil refineries, wood treatment plants and municipal sewage treatment facilities are located around numerous estuaries in northeastern North America. Spoils from dredging activities may impact fish (Zitko 1995). Pollution may result in immunosuppression of fish thus making them more susceptible to disease (Arkoosh et al. 1998).

Density dependence - Density independent.

Geographic scope - Throughout the salmon's range, but most likely to occur in southern areas which are more industrialized.

Probable change since 1984 - Reductions of industrial activities and improvements in effluent treatments should have improved the situation.

Evidence - State of the environment reports by Environment Canada and ongoing monitoring programs should provide measures of effluent loads, chemical composition and changes over time resulting from modifications in effluent treatments.

Tests - Grow-out experiments after exposure to estuarine waters to assess the acute and chronic effects of estuarine pollution on smolt survival, bioassays exposing smolts to suspected contaminants.

Consequences if true - Deleterious estuarine conditions may aggravate already low at-sea survivals of salmon. Recovery of salmon stocks may be delayed or hampered.

Potential for intervention - If demonstrated, measures to reduce the impacts of effluents could be considered (for example, limiting the discharge during migration periods.

IV.6.b. Exposure to endocrine disrupting compounds compromise the parr-smolt transformation (G. Chaput, D. Meerburg)

Hypothesis - Exposure of salmon to exogenous estrogenic and/or androgenic substances during parr-smolt transformation compromises subsequent sea water adaptability and survival.

Background - Several investigators have shown that the parr-smolt transformation and subsequent sea water adaptability were impaired by exogenous treatments with gonadal steroids (Lundqvist et al. 1989, Madsen and Korsgaard 1989). Fairchild et al. (1999) suggested a link between past pesticide use and declines of some Atlantic salmon populations. The estimated levels of 4 nonyl phenol (4-NP) present after forest spraying were similar to those currently found in industrial effluents, pulp mill discharges and municipal sewage outfalls (Bennie et al. 1998). Long-range atmospheric transfer is also a potential means of delivering endocrine disrupting compounds to salmon.

Density dependence - Density independent.

Geographic scope - Wide. Forest spraying occurs throughout much of the freshwater range of Atlantic salmon. North American air masses tend to move northeast, bringing atmospheric contaminants from industrialized areas to the range of Atlantic salmon. Potential effects are most likely in densely populated estuaries with industrial development.

Probable change since 1984 - Unknown. Sewage treatment facilities generally do not remove endocrine disrupting compounds and may concentrate the effluent at point discharges at mid-channel or other locations which fish might frequent.

Evidence - see Background.

Tests - Conduct laboratory exposure experiments with subsequent grow-out to assess the effects of estuarine waters to short-term (several months) survival and growth. Compare sea survival rates of smolts released after being held in estuarine water, artificially contaminated water, and clean water. Test for atmospheric transport by assays in waters which do not receive local contaminants.

Consequences if true - Deleterious estuarine conditions may exacerbate already low marine survival of salmon. Salmon stocks may undergo further declines or recovery may be delayed or hampered.

Potential for intervention - Effluent inputs can be reduced. Reduction of atmospheric contaminants may require international cooperation.

IV.6.c. Low pH of rivers decreases survival of descending smolts (P. Amiro)

Hypothesis - See II.6.a and III.6.b.

Background - See II.6.a and III.6.b.

Density dependence - Density independent.

Geographic scope - See II.6.a and III.6.b.

Probable change since 1984 - See II.6.a and III.6.b.

Evidence - See II.6.a and III.6.b.

Tests - See II.6.a and III.6.b.

Consequences if true - See II.6.a and III.6.b.

Potential for intervention - See II.6.a and III.6.b.

Sources - See II.6.a and III.6.b.

IV.7. Environment - physical/biological

IV.7.a. Dams reduce the number of smolts reaching the estuary (L. Marshall and P. Amiro)

Hypothesis - The number of smolts reaching estuaries of impounded drainages has decreased because there are more dams, less water and fewer fish bypassing turbines (Hvidsten and Hansen 1988), or more predators.

Background - Hydro dams have headponds with slower-than-river transport velocities and generally lack surface exits suitable for fish. Water flow is generally through deep-entry tunnels leading to turbines. Slow headpond velocities result in longer exposure of pre-smolts to predators while in transit. The absence of surface exits at dams results in: delays of smolt downstream passage affecting potential critical windows of survival at sea; pre-smolts failing to reach favorable riverine overwinter habitat; possible loss of smolt physiological characteristics related to salt water adaptation, additional exposure to predators (McCormick et al. 1999, Whalen et al. 1999) and possibly another year of mortality in freshwater. Turbines kill fish (AFS 1993). All factors contribute to diminishing returns (Blackwell et al. 1998).

Density dependence - Density independent with the exception where numerous pre-smolts/ smolts might attract fish or avian (Blackwell 1996) predators.

Geographic scope - Will affect salmon in those drainages having hydroelectric projects with upstream passage for adults.

Probable change since 1984 - Unlikely that losses because of dams have increased, with the exception of the occasional new small hydro project. River discharge patterns and associated patterns of power production may have changed. Predator fish populations in headponds or predator avian populations proximate to tailraces may have matured/ expanded over time.

Evidence - There are no significant additions to the inventory of dams since 1984. Existing dams and power houses are unlikely to have changed their pattern of operation sufficiently to explain the decline in adult returns. Predator populations have likely increased in a few locations (largely undocumented), but are likely to impact only a few stocks.

Tests - Update stock status of headpond fishes; review operational procedures at hydroelectric facilities for generation or spill patterns during pre-smolt/ smolt migrations; examine changes in flow and spill patterns through hydrological records.

Consequences if true - Salmon declines will continue.

Potential for intervention - Ensure spill or low-mortality generation for daily windows when smolts have accumulated in forebays (Washburn & Gillis 1995), install appropriate downstream passage at dams, encourage the harvest of headpond predators, trap and truck pre-smolts/smolts around dams, remove dams.

IV.7.b. Alterations in discharge regimes reduce the ability of smolts to reach the estuary (D. Caissie and D. Cairns)

Hypothesis - Flow alteration due to dams, other artificial obstacles, water withdrawal and land use practices reduces the ability of smolts to successfully descend rivers.

Background - Salmon rivers commonly experience peak discharge rates in spring (Poff et al. 1997). Water control structures on rivers may dampen fluctuations in discharge rate. In the case of hydro dams, they may also intensify fluctuations if water intake is varied in response to short term changes in electricity demand. Deforestation for logging or other purposes tends to increase the intensity of fluctuations. Discharge rate and water temperature are important determinants of smolt migration timing (Ruggles 1980, Cunjak and Randall 1993). Hence changes in the pattern of discharge may affect the timing of downstream smolt movements. Smolts which arrive in the estuary at an inappropriate time in their physiological cycle may experience increased difficulty in osmoregulatory adaptation (McCormick et al. 1999, Whalen et al. 1999). Extreme flood events during smolt migration might also cause physical damage to smolts if water velocities exceed the ability of the fish to maintain a controlled descent while avoiding contact with debris and the substrate.

Density dependence - Density independent.

Geographic scope - In general, anthropogenic effects on flow regimes are greatest in the southern, more populated part of the salmon's range.

Probable change since 1984 - Mixed (see I.7.c). Overall, there is probably little net change in the degree to which flow regimes in salmon rivers have been altered by human activities.

Evidence - There is no evidence for widespread alteration of flow patterns which might affect the ability of smolts to descend rivers.

Tests - Effects of changes in discharge patterns on smolt migration could be tested by comparing the timing of smolt runs in relation to the timing and the intensity of peak flows. Success of smolt descent under various hydrological conditions could be tested by marking fish at headwater streams and recapturing them in the lower rivers and comparing results across rivers and years. The degree to which anthropogenic effects contribute to extreme flow events could be determined through hydrological models.

Consequences if true - Salmon declines will continue in rivers where anthropogenic flow alteration continues.

Potential for intervention - Modify water releases from water control structure to better reflect the natural river discharge during the incubation period. Alter land-use practices to reduce spring run-off.

IV.7.c, V.7.c. UV exposure in freshwater or in estuaries reduces survival of smolts (G. Chaput and D. Cairns)

Hypothesis - Increasing exposure to radiation during freshwater rearing or estuarine passage causes metabolic damage that results in increased mortality during smoltification, adaptation to salt water, and marine migrations.

Background Walters and Ward (1998) elaborated this hypothesis with respect to UV exposure while in fresh water. Potential effects of UV radiation include depression of aquatic productivity, physiological effects including sunburn, suppression of immune responses and egg mortality.

Density dependence - Density independent although increasing abundance of juveniles may force a proportion of the population into poorer habitats that are less shaded.

Geographic scope - May affect salmon throughout its range in eastern North America. According to Walters and Ward (1998) effects are likely to be most intense in southern regions where there is more solar radiation and least intense in the north where there is less.

Probable change since 1984 - UV radiation has probably increased due to the thinning of the ozone layer.

Evidence - Declines in sea survival of Pacific salmon have been more severe in sunny areas. Salmon declines have been more severe in Quebec and New Brunswick than in Newfoundland.

Tests - Conduct controlled experiments in hatcheries by rearing fish under variable UV exposure conditions followed by sea-water challenge tests or grow-out experiments (at aquaculture sites for example). Install monitoring equipment at key locations to measure UV radiation variability.

Consequences if true - As stated by Walters and Ward (1998), if the hypothesis is correct, "marine survival rates may not recover even if ocean conditions return to normal."

Potential for intervention - Put UV-opaque covers over outdoor tanks in hatcheries. Strengthen measures to encourage or require vegetated streamside buffers that will shade stream waters. Reduce human ozone-depleting activities.

IV.8. Environment - thermal

IV.8.a. Alterations in spring temperature regimes increase smolt mortality (D. Caissie)

Hypothesis - Abnormally warm temperatures in the spring affect the timing of the smolt exodus, resulting in higher mortality.

Background - Discharge rates and water temperature are important determinants of the timing of downstream migration of smolts. Hence if rivers warm earlier, then the smolt run will tend to occur earlier.

Density dependence - Density independent.

Geographic scope - Generally in the southern part of the salmon's range.

Probable change since 1984 - Uncertain.

Evidence - Timing of smolt exodus is strongly influenced by temperature (Ruggles 1980, Whalen et al. 1999). Hence warm and early springs will likely produce earlier smolt runs. If the thermal regime in rivers is advanced, but the thermal regime in the sea is not, it is possible that smolts entering the sea will not be adapted for the conditions they encounter there (McCormick et al. 1999).

Tests - Compare sea survival of smolts among years and rivers with varying timings of spring.

Consequences if true - If the hypothesis is true, salmon declines could continue as a result of potential global warming.

Potential for intervention - If hydraulic structures (e.g. ponds, dams) contribute to higher water temperatures, such effects could be reduced by modifying water release patterns. If high water temperatures are due to global warming, decrease emissions of greenhouse gases.

V. OCEAN LIFE

V.1. Fisheries

V.1.a. Commercial fisheries in Greenland harvest more salmon than is officially reported (G. Chaput and L. Marshall)

Hypothesis - Commercial fisheries in Greenland continue to take a significant proportion of the salmon at sea, formerly as reported catch and now as unreported catch.

Background – Through the auspices of NASCO, salmon quotas have been reduced from a high of 1,191 t in 1972-1983 to a low of 20 t in 1998 (Anon. 1999a). Critics suggest that even though all salmon caught by Greenlandic fishermen which are destined for distant markets must go through government fish plants, sales for local consumption are largely unmonitored and possibly more extensive than reported.

Density dependence - Density independent, except at low levels of stock abundance when effort may be density dependent.

Geographic scope - May affect MSW (but not 1SW) salmon throughout its range in eastern North America, (excluding inner Bay of Fundy).

Probable change since 1984 - Harvests in Greenland have decreased.

Evidence – No concrete evidence. Catch statistics (Anon. 1999a), estimates of reported landings, changes in allocation procedures, licensing, low market value for the product and single government clearing house for access to international markets, international agreements (NASCO) and investigations (Anon. 1999b) and logistics of hiding a significant "food fishery" all suggest that declines in reported and estimated unreported landings are consistent with economic times and fishery management measures in place.

Tests - Quantify the missing MSW returns as non-maturing 2SW fish under the assumption that 1SW:MSW ratio among returns to North America has changed only because of the cropping of non-maturing 2SW fish in Greenland and propose how such a harvest would go unseen in West Greenland.

Consequences if true - Declines of 2SW salmon will decrease until the Greenland fishery is effectively curtailed.

Potential for intervention - Full monitoring and enforcement of the Greenland fishery.

V.1.b. Undocumented commercial fisheries reduce marine survival (G. Chaput, L. Marshall, and D. Cairns)

Hypothesis – Post smolt and adult salmon are taken in directed pirate fisheries, or as bycatch in fisheries that target other species.

Background – Dadswell (2000a, b; see also Thurston 1994) argued that the decline in Atlantic salmon may be due to unreported fisheries harvest in the offshore zone, especially outside the 200 nautical mile Economic Exclusion Zone. Drift-nets were a major gear type during the days of large scale salmon fishing off Greenland (Christensen and Lear 1980). Vessels that could potentially prosecute a modern-day unreported salmon fishery include the Pacific fleet that formerly fished very long (up to ca. 60 km) drift-nets, which were banned from the world's oceans by United Nations resolution in 1992 (Meerburg 1994, Thurston 1994). Vessels flying flags of convenience currently operate a major illegal fishery for tuna in the Atlantic Ocean (ICCAT 1998-1999). The presence in the Atlantic of "pirate" vessels operating outside any regulatory or monitoring system increases the scope for unreported fisheries on Atlantic salmon. The extent to which salmon of North American origin visit waters of the central and eastern Atlantic is poorly known, but might be greater than previously recognized (Tucker et al. 1999).

In some parts of the Northeast Atlantic, herring, mackerel, and post-smolt salmon have overlapping distributions during part of the year, leading to suggestions that herring and mackerel trawl and purse-seine fisheries could take significant numbers of salmon (Anon. 1999a, 2000). Salmon might therefore be an undetected component of North Atlantic trawl fisheries for shrimp, capelin and other pelagic species.

Cairns and Reddin (2000) showed that seals and seabirds could harvest a high proportion of marine-phase Atlantic salmon even if salmon are a very small fraction of the diet of these predators. This is due to the fact that biomass of marine-phase salmon is extremely small relative to total food consumed by seals and seabirds. The same logic could apply to fisheries; i.e. a fishery with large total landings might harvest a substantial portion of salmon biomass even if salmon are a small proportion of catch.

Density dependence – For directed fishing, density dependent because fishing for salmon will become uneconomical if catch rates are low.

Geographic scope - Would affect salmon throughout its range in eastern North America (probably excluding the Inner Bay of Fundy).

Probable change since 1984 - Decreased potential for unreported commercial salmon harvest because of the reduction of overall commercial finfishing effort, improved surveillance through observer programs, closure of many "cover" fisheries and the declining value of wild salmon. However, there appears to have been an increase in the number of vessels in the Atlantic that have adopted flags of convenience in order to prosecute unsanctioned fisheries.

Evidence – There is no direct evidence to support this hypothesis (Meerburg 1994). There is no evidence that vessels engaged in the illegal high-seas tuna fishery also prosecute a targeted fishery for Atlantic salmon. If long drift-nets of the type that were used in the North Pacific are currently used to fish salmon in the North Atlantic, there would likely be tangles with ship propellers and long sections of netting would drift at sea. If the fishery occurred in the Labrador Current, such gear would be carried south into shipping lanes, fishing zones, and populated areas where it would be seen. Such incidents have not been reported from the north-west Atlantic (Meerburg 1994).

Tuna are a high-value fish, but the market price of salmon has decreased because of large volumes of aquaculture production. Given the low price of salmon, a pirate drift-net fishery for salmon in the Northwest Atlantic would be economically viable only if catch rates are high.

Dempson et al. (1998) compiled numbers of salmon caught in demersal and mid-water trawl fisheries in waters off Newfoundland and Labrador. Research vessels captured 27 salmon in approximately 600,000 sets between 1965 and about 1998. Fisheries observers on commercial trawl vessels recorded 22 salmon from 424,490 sets between 1980 and 1997. The very low incidence of salmon in these records suggest that salmon are in very low density in the areas where these fisheries operated, that trawls are a very inefficient means of catching Atlantic salmon, or both of the above.

Using surface-set gillnets in the Labrador Sea, Reddin and Short (1991) caught a mean of 1.04 salmon per nautical mile of net per hour in fall 1987, and 2.98 salmon per nautical mile of net per hour in fall 1988.

Tests – Evaluate the incidence over time of net-marked salmon in monitoring facilities in rivers. Using salmon catch rates from research fisheries and monitored commercial fisheries, and records of total commercial fishing effort, estimate total salmon bycatch in sanctioned fisheries for 1984-present. Use catch rates recorded in waters outside Economic Exclusion Zones and market prices to evaluate the potential economic viability of pirate fishing for salmon. Investigate the possibility of mis-identification of salmon by observers. Investigate the avenues available for illegally caught salmon to be absorbed into the marketplace. Quantify recent changes in non-salmon gear in waters where it may intercept salmon. Examine satellite images for evidence of unreported fishing activity outside the Economic Exclusion Zone.

Consequences if true - Salmon will continue to decline until the unmonitored harvests are reduced or eliminated.

Potential for intervention - Aircraft patrols/ satellite monitoring, international observer programs to provide a basis for the curtailing unreported salmon harvest.

V.1.c. Natural mortality after commercial fisheries is higher than presumed, which means that the reduction in pre-fishery abundance is overstated (D. Meerburg, D. Cairns, and G. Chaput)

Hypothesis - Natural mortality between the 1SW and 2SW years is greater than that postulated in fisheries models and varies annually. This means that the reduction in fishing mortality due to the progressive closure of fisheries has had less effect on total mortality than assumed by models. Consequently, the expectation of improved salmon returns following fisheries closures has been unrealistically high and the declines in pre-fishery abundance have been overstated.

Background - The widely reported decline of Atlantic salmon in the Northwest Atlantic is based on estimates of pre-fishery abundance (PFA). PFA is the estimated number of salmon alive at sea in the first sea winter prior to any fishery on 2SW fish. Estimates of total North American river returns have declined only modestly since the mid 1980s (Anon. 2000).

Commercial fisheries for North American salmon have been sharply curtailed, and in most areas, eliminated. As these fisheries were reduced, there was an expectation that most of the production formerly taken as commercial catch would subsequently be available for return to rivers. Models used to estimate pre-fishery abundance assume that 1% of salmon die each month from natural causes after the first winter at sea (Anon. 1999a, Potter and Crozier 2000). This may be lower than actual natural mortality rate. Lorenzen (1996) estimated natural mortality of marine fishes from their weight as $M_u=aM^b$, where $a = 3.69$ and $b = -0.305$. Application of this formula to salmon between 1SW and 2SW gives an annual mortality of 27%. Cairns and Reddin (2000) showed that mortality of marine-phase salmon that return as grilse is much higher than that of typical fish of similar weight. This suggests that natural mortality of 1SW and 2SW salmon might be substantially higher than that estimated by the Lorenzen (1996) formula.

An incorrect assumption for natural mortality in the modelling of prefishery abundance will bias the estimates under fishing and non-fishing scenarios. The following example illustrates the bias. Assume the true PFA is 10,000 animals. The sea fishery takes 50% of these and the remaining animals have a natural mortality rate of 10% between the point of the fishery and being enumerated in the rivers. In the rivers, a total of 4,500 animals are counted (10,000 * (1-0.5) * 0.9). The PFA model assumes that the natural mortality between the point of the fishery and counts in the rivers is 10%. The PFA estimate of abundance is simply the counts in the rivers adjusted for a natural mortality of 10% plus the fisheries catch. For the case of a fishery, the PFA estimate is 10,000 fish and unbiased (4,500 / 0.9 + 5,000). In the absence of a fishery, of the 10,000 fish alive at the PFA point of estimation, 90% will survive and return to the rivers (i.e. 9,000 fish). The estimated PFA based on the return of 9,000 fish equals 10,000 and is also unbiased (9,000 / 0.9). Whether a fishery occurs or not, the PFA estimate is unbiased because the actual M and assumed M are equal.

	Assumed M = Actual M		Assumed M < Actual M	
True PFA	10,000	10,000	10,000	10,000
Fishing rate	0.5	0	0.5	0
Fishery survivors	5,000	10,000	5,000	10,000
True M	0.1	0.1	0.5	0.5
River returns	4,500	9,000	2,500	5,000
Assumed M	0.1	.1	0.1	0.1
Predicted PFA	10,000	10,000	7,778	5,556
Error	0%	0%	-22%	-44%

On the other hand, if the actual natural mortality rate is different from the assumed, then the PFA estimate will be biased. In this example, the actual natural mortality rate between the PFA point of estimation and the river return is 50% while the model assumes the natural mortality rate at 10%. Under the fishing scenario above, of the 5000 fish surviving the fishery, only 50% will survive to be counted into the rivers, i.e. 2500 fish. Using this starting value, the PFA estimate under the fishing scenario is about 7800 fish (2500 / 0.9 + 5000) or 22% less than the true PFA value. In the absence of a fishery, there is a more severe bias, 44% below the true PFA because of the 5000 fish not caught in the fishery, 50% of them will die before returning to the rivers whereas the model assumes that only 10% would have died.

Density dependence - density independent

Geographic scope - May affect salmon throughout its range in eastern North America.

Probable change since 1984 - If natural mortality is underestimated, impact of harvest reductions would be overestimated during the period when fisheries have been reduced and the estimated PFA is negatively biased, i.e. the true decline in PFA abundance of salmon is less than reported.

Evidence - No direct measurements of mortality between 1SW and 2SW are available. The hypothesis is consistent with the failure to see clear increases in returns following major fisheries reductions.

Tests - Investigate the sensitivity of currently used models to changes in assumed natural mortality; review return expectations if natural mortality has been higher than assumed.

Consequences if true - The decline in estimated PFA is, in part, an artifact of an erroneous assumption in the PFA model. The error is likely to be particularly high in MSW fish which are exposed to marine mortality risk for a longer time than 1SW fish.

Potential for intervention - Revise PFA models.

V.2. Aquaculture

V.2.a. Aquaculture escapees compete with wild salmon for resources in the ocean (J. Ritter)

Hypothesis - Aquaculture escapees compete with wild salmon for food resources in the ocean and thereby reduce marine survival.

Background - Wild Atlantic salmon in the sea are now vastly outnumbered by aquaculture salmon held in net-cages (Gross 1998). Escapes of aquaculture fish are poorly documented, but the number of escapees is thought to be substantial, at least in some years and in some locations. There is very little information on the longevity and marine migrations of escapees from aquaculture. Potential for competition exists from escapees from both freshwater hatcheries and marine cages (DFO 1999b).

Density dependence - Density dependent; the greater the density of wild salmon, or abundance of escapees, the greater the potential for competition for food resources.

Geographic scope - Potential for competition would be greatest for the inner Bay of Fundy stocks which spend their marine life in and near the Bay of Fundy and in close proximity to the main part of the salmon aquaculture industry in eastern North America (Ritter 1989, DFO 1999b).

Probable change since 1984 - Potential for competition increased with the dramatic growth of the industry during the late 1980s and through the 1990s.

Evidence - No direct evidence.

Consequence if true - Reduced marine survival.

Potential for intervention - Improved containment of salmon in hatcheries is feasible with implementation of compliance monitoring. Better containment in marine cages is also feasible but will never be complete.

V.3. Disease

V.3.a. Disease and parasitism reduce marine survival (J. Ritter)

Hypothesis - Disease and parasitism reduce the survival of wild Atlantic salmon while in the sea.

Background - Fish disease agents potentially of concern and identified in wild Atlantic salmon of the

Maritimes include *Renibacterium salmoninarum* (Bacterial Kidney Disease), *Aeromonas salmonicida* (furunculosis), *Yersinia ruckeri* (responsible for enteric redmouth), *Vibrio anguillarum* (vibrio), infectious pancreatic necrosis virus, *Edwardsiella tarda* and sea lice parasites (*Caligus* sp. and *Lepeophtheirus* sp.) (DFO 1999b). All the agents identified in wild stocks have been found in farmed salmonid populations in the Maritimes, as well as *Vibrio salmonicida*, proliferative kidney disease agent (PKD), *Enterocytozoon* sp. and infectious salmon anemia virus. The prevalence of these and other agents in North American farmed and wild salmon is reviewed by MacKinnon et al. (1998).

Density dependence - Likely to be density independent in the open sea but both density independent and density dependent effects might operate relative to some pathogens in confined areas such as estuaries.

Geographic scope – Unknown, because sampling is generally done on juveniles and adult fish while in fresh water. Even sampling in fresh water is inadequate to assess the distribution and severity of diseases among wild Atlantic salmon in North America (MacKinnon et al. 1998).

Probable change since 1984 - Unknown because sampling is inadequate/ non-existent.

Evidence - No evidence exists of epidemics occurring in wild salmon populations at sea. Current furunculosis epidemics are only apparent in fresh water (MacKinnon et al. 1998).

Wild salmon are often infested with sea lice in the marine environment but their effect on wild salmon survival is unknown. There is evidence in Europe that farmed salmon have higher lice levels than wild salmon on the ocean feeding grounds and that lice on farmed salmon contribute to lice on local wild salmonid stocks but the consequences of this are still unknown (McVicar 1998).

Consequence if true - Consequences would be reduced marine survival. However, the absence of common overt symptoms in fish captured in numerous monitoring traps and by fisheries argues against disease and/or parasitic agents being responsible for the current low marine survival experienced by many North American salmon populations.

Potential for intervention - Eradication of disease-infected and parasite-infested cultured stocks and improved husbandry to prevent infection and dissemination of disease causing agents would reduce the risk of disease outbreak in wild salmon populations.

V.4. Predation

V.4.a. Predation by other fish reduces marine survival (L. Marshall)

Hypothesis - Atlantic salmon survival has decreased because fish predation has increased due to large-scale changes in the marine environment of the Northwest Atlantic.

Background – There have been changes in large marine ecosystems in the marine range of Atlantic salmon (Rice 1999, Pederson and Rice 1999, Zwanenburg et al.1999). There is the possibility that the niches of some commercially important over-fished stocks have been back-filled by new and more serious predators of salmon e.g., sharks, or that predators have moved or expanded their range into the proximity of salmon, or that migration routes of salmon have shifted to waters with high predation risk from fish.

A decline in ocean temperatures (DFO 1997), a positive correlation between the abundance of salmon and a temperature-based index of marine winter habitat for salmon (Anon. 1999a), and devastating declines in the abundance of northern cod and other species (DFO 1998c), suggest that there are changes to the salmon's marine ecosystem which may have affected survival. Post smolts are likely the most vulnerable stage for predation by other fish.

Density dependence - Density dependent, i.e., mortality increases with increased abundance of new predators.

Geographic scope - Unlikely to affect potential 1SW and MSW salmon throughout their range in eastern North America, unless by coincidence, different predators of salmon in the different large marine ecosystems increased in synchrony.

Probable change since 1984 – Probability of change in predation in Gulf of St. Lawrence, Newfoundland and Labrador Shelves is unknown. The acknowledged decline in groundfish predators (cod; offshore, but perhaps not inshore: DFO 1999c,d) in some areas and potential increase in other areas is inconsistent with a large scale effect of fish predators depressing marine survival.

Evidence – No direct evidence. The reduced abundance of most commercially fished potential predators, such as cod, is contrary to the hypothesis. The hypothesized increase in less harvested predators, e.g., dogfish sharks in Gulf of Maine and Scotian Shelf requires verification.

Tests - Examine relationships between trends in indices of salmon survival and trends in abundance of potential predators in various large marine ecosystems thought to be utilized by smolts, post smolts, and adults.

Consequences if true - Salmon abundance will continue to decline. A rebuilding of groundfish stocks could exacerbate the problem if groundfish are major salmon predators, but it could alleviate the problem if recovering groundfish populations displace other fish (e.g. dogfish) which are salmon predators.

Potential for intervention – Fishing patterns probably have major ecosystem effects, but it is not clear what fishing management measures would give the best chance of reducing predation pressure on salmon.

V.4.b. Predation by birds and marine mammals reduces marine survival (D. Cairns)

Hypothesis - Predation by birds and marine mammals has reduced survival of Atlantic salmon at sea.

Background - The main potential avian predators of marine-phase salmon are gannets, murres, kittiwakes, shearwaters, gulls, and fulmars (Cairns and Reddin 2000). Among marine mammals, potential predators include the main seal species of eastern Canada (harbour, grey, harp, hooded) and cetaceans, particularly toothed whales.

Seals and seabirds are for the most part opportunistic predators which take any prey within a given size range. Seals can take salmon of any size range, although it is unclear whether the large size of adult salmon reduces their vulnerability to seal predation (Cairns and Reddin 2000). Seabirds take only post-smolt salmon, but the number of seabird species capable of harvesting post-smolts declines as the fish grow in their post-smolt year (Cairns and Reddin 2000).

In general, salmon appear only in trace amounts in the diets of seabirds and seals in the Northwest Atlantic (Cairns and Reddin 2000). An exception is the northern gannet, a large plunge-diving seabird which breeds in eastern Newfoundland and in the Gulf of St. Lawrence. Because of the gannet's specialized feeding technique, salmon appear to be more vulnerable to this predator than to any other seabird or seal (Montevecchi et al. submitted)

Density dependence - Density independent. Salmon are rare in the sea and constitute only a minute fraction of finfish biomass in the Northwest Atlantic. Therefore intraspecific competition is unlikely, and compensatory mechanisms based on reduction of competition are unlikely to reduce the effects of predation removals. Because of the salmon's rarity, it is unlikely that density-dependent predator attraction or predator swamping will occur.

Geographic scope - Wide. Potential seabird and marine mammal predators are present throughout the entire range of Atlantic salmon in the northwest Atlantic.

Probable change since 1984 - Populations of gannets breeding in eastern Canada rose 96% between censuses conducted in 1984 and 1999. Populations of most other species of seabirds breeding in the northwest Atlantic are stable or rising (Chardine et al. 1999). Population trends for long distance migrants (shearwaters, fulmars) are unknown. Numbers of the four major seal species in eastern Canada (harbour, grey, harp, hooded) have risen since 1972 and substantially since 1984 (Hammill and Stenson 1997).

Evidence - Gannets breeding on Funk Island, Newfoundland, are estimated to have consumed a mean of 0.3% and 3.1% of North American post-smolts during August in the 1980s and 1990s, respectively (Montevecchi et al. submitted). Total salmon consumption by North American gannets cannot be calculated because diet data are available for Funk only for August, and are sparse or unavailable for other colonies.

The Funk gannetry comprises 13% of the North American population. If salmon contribution to diet of Funk gannets in the 1990s also applied to other colonies and to months other than August, gannets may have consumed a substantial fraction of North American post-smolts in the 1990s.

Apart from gannets, only 10 records of salmon predation have been reported from seabird and seal stomachs in eastern Canada (murre: 1; harbour seal: 1; harp seal: 2; grey seal 6, but some of the grey seal records may have involved net-robbing) (Cairns and Reddin 2000). This indicates that salmon are of inconsequential importance in the diet of seabirds and seals in eastern Canada. However, it does not necessarily follow that consumption by these predators is inconsequential to salmon. Annual consumption by seabirds and seals in eastern Canadian waters is about 6.2 million tonnes (seabirds: 2.4 million tonnes, Diamond et al. 1993, Cairns and Reddin 2000; harp seals: 3.1 million tonnes, other seals: 0.7 million tonnes, Hammill and Stenson 1997). Biomass of post-smolt salmon in August was estimated to average 728 tonnes during the 1990s. This means that predators could exert a high exploitation rate on salmon populations even if salmon are a minute fraction of the predators' diets. For example, if post-smolt salmon were 0.24% of harp seal diet in their period of geographic overlap in fall, then the entire post-smolt cohort would be consumed (Cairns and Reddin 2000).

The only record of salmonid consumption by cetaceans in eastern Canada is from a single salmonid otolith found in a harbour porpoise stomach. In the absence of cetacean consumption estimates, it is not possible to model potential impact of cetacean predation on salmon. However, annual food harvest by cetaceans in nearby regions is very large (1.9 million t in northeastern US, Kenney et al. 1997; 6.1 million t in Icelandic and adjacent waters, Sigurjonsson and Vikingsson 1998). This suggests that cetacean predation could have a substantial impact on salmon even if salmon are only a minute fraction of cetacean diet.

Because reliable estimates of salmon consumption by seabirds and marine mammals (other than gannets) do not exist, the hypothesis cannot be confirmed or refuted. However, the hypothesis can be considered plausible because seal populations in northeastern North America have risen substantially since 1984, and populations of gannets and some other seabirds have also risen.

Tests - Potential tests of this hypothesis are reviewed by Cairns (2001). For gannets, total current harvest of post-smolt salmon could be estimated via bioenergetic models, using dietary data with full spatial and temporal coverage of North American gannetries. The relation between gannets and the salmon decline cannot be directly evaluated because gannet diets in previous years cannot be measured. However, if gannets currently take a significant proportion of North American post-smolts, the hypothesis would become more plausible.

For seals and for non-gannet seabirds, no direct test is immediately available. Conventional bioenergetic analysis requires reliable estimates of salmon as a portion of predator diet. Such estimates are not attainable because they would require huge sample sizes, beyond the limit of feasibility. The best short-term approach may involve i) improvement of current diet studies, so that evidence of salmon predation is not overlooked as it sometimes has been in the past, and ii) derivation of insight from predation studies at finer scales (e.g. estuaries). In the long term, a practical means of testing the hypothesis is unlikely to emerge without improved basic knowledge of the distribution, migratory patterns, and ecology of salmon at sea. Potentially fruitful methods include acoustic telemetry, fisherman questionnaires, gannet sampling, and research fishing to help clarify post-smolt movements, analysis of scale and otolith patterns to investigate relations with oceanographic conditions, and use of electronic recorders to track behaviour at sea.

Consequences if true - Salmon returns will continue to decline if predator populations remain at present levels or continue to rise.

Potential for intervention - Predation pressure could be reduced by predator culls or increased predator harvests. However, such programs would encounter strong opposition.

V.4.c. Marine survival has decreased because cooler waters have altered the temperature-mediated balance between endothermic predators and ectothermic prey (D. Cairns)

Hypothesis - The decline in North American Atlantic salmon has been caused by the synergistic effects of cold water and predation by marine endotherms, according to the following causation chain:

a) water cools,
b) endothermic predators increase in population because cold water gives them a relative advantage over ectothermic prey,
c) predation on salmon increases because
  i) numbers of endothermic predators are higher,
  ii) cold water gives endothermic predators an increased advantage over salmon which are ectothermic, and
  iii) salmon must spend more time in the warm surface layer, where predation risk is high, in order to achieve target growth rates.

Background - This hypothesis rests on two concepts which have not yet been developed in the literature. These are summarized as follows:

a) *Growth-mortality trade-offs in marine-phase salmon.* In freshwater, Atlantic salmon display growth rates which are typical of other fish occupying similar habitats. Once salmon enter the sea, growth rates increase dramatically. Salmon increase approximately 75-fold in weight between smolt exodus and return as 1SW adults, and 213-fold between smolt exodus and return as 2SW adults (figures from Cairns and Reddin 2000). These growth rates appear to be the most rapid of any pelagic fish in the Northwest Atlantic.

Pauly (1980) showed that natural mortality in fishes is closely and positively related to growth rate. This suggests that there is a trade-off between mortality and growth. The interspecific effect demonstrated by Pauly (1980) may also occur within species. High latitude populations of striped bass and silversides have more rapid inherent growth rates than low latitude ones (Conover et al. 1997). High growth rates must have a cost, otherwise all fish would grow at the maximum observed rate. The most likely explanation for this is that rapid growth rate is accompanied by high mortality risk.

The chief environmental determinants of growth in fishes are temperature and food availability. During summer, the surface layer of the Northwest Atlantic is much warmer than deeper layers. This gives fish the opportunity to practice behavioural thermoregulation, in a manner akin to reptiles basking in the sun. Thus salmon occupy the surface layer to increase body temperature, and leave this layer as needed to forage for food. Heat increments obtained at the surface will also keep the body above ambient temperature for a period of time following descent into cooler layers.

In the ocean environment, demersal fish use depth as cover, and pelagic species that swim at the surface form dense schools to reduce predation risk (Sogard and Olla 1997). It is probable that marine-phase Atlantic salmon have always had very low populations compared with those of other pelagic fishes that occupy the same habitat (herring, mackerel, capelin). Relatively low numbers and diffuse migratory pathways (Cairns and Reddin 2000) may constrain the ability of salmon, particularly post-smolts, to use schools to reduce predation risk while swimming at the surface. Hence surface basking may be the behaviour where the growth-mortality trade-off operates, because surface basking offers a temperature-mediated growth advantage but heightens predation risk.

Sizes of returning salmon have been relatively stable over the period of increasing natural mortality in the sea (see V.7.b). The relative stability of returnee weights over a wide range of mortality conditions implies that salmon have target weights for 1SW and 2SW return. Fish may adjust their behaviour to reach these targets (behavioural buffering; Burger and Piatt 1990). When growth conditions are favorable, they feed and bask enough to maintain their target growth rates; the remainder of the time they adopt predation-averse behaviours such as descending in depth. When growth conditions are poor, they feed and bask at higher rates, thereby maintaining growth targets but at the same time suffering higher mortality risk.

b) *Temperature controls the balance of advantage between endotherms and ectotherms.* Adult salmon entering rivers commonly bear scars that are apparently inflicted by seals (Baum 1997). This suggests that at least some salmon escape predation attempts.

The ability of salmon to escape a predatory attack is linked to its reaction time and swimming speed. In aquatic ectotherms, performance of nervous and muscular systems is strongly influenced by ambient temperature (Lin and Regier 1995). Although cold-water fishes have biochemical adaptations that mitigate temperature effects on enzyme systems, burst speeds and reaction times decline steeply with temperature (Johnston et al. 1991). Booth et al. (1997) reported that wild adult salmon showed higher sustained swimming speeds at 18°C than at 12°C, but peak speeds over 10 second intervals did not differ between these temperatures. Swimming performance of marine endotherms is unaffected by ambient temperature because internal temperature is constant.

The depressed swimming performance of ectotherms at low temperatures means that endothermic predators have an advantage over ectothermic prey in cold water. The relative balance between endothermic predators and ectothermic prey is reflected in the worldwide distribution of seals and pursuit-diving seabirds. These animals are virtually absent in the tropics (except in areas of cold-water upwelling), moderately abundant in temperate zones, and very abundant in polar zones (Lavigne et al. 1989). This pattern cannot be explained by the distribution of productivity because seals are absent from many tropical areas which are highly productive (Berger and Wefer 1991).

Density dependence - Density independent.

Geographic scope - Wide, because all anadromous North American Atlantic salmon (except inner Bay of Fundy stocks) appear to use the Newfoundland-Labrador Shelf area.

Probable change since 1984 - Temperatures on the Newfoundland Shelf declined sharply in the late 1980s and early 1990s, but have since recovered (Colbourne 1999a). Numbers of seals and of some seabirds have increased since the 1980s (Cairns and Reddin 2000).

Evidence - Records from electronic data loggers attached to salmon in Newfoundland and Iceland (Sturlaugsson 1995, Reddin et al. 1999) suggest vertical movements which may represent alternation between surface basking and foraging dives in accordance with the growth strategy proposed above.

Comparison of marine-phase salmon biomass and food harvest of seals and seabirds indicates that high endotherm exploitation rates are plausible even if salmon are rare in their diets (Cairns and Reddin 2000).

The hypothesis posits three triggers for higher salmon predation. One of these is increased predator numbers. Since seals and seabirds are long-lived animals, their numbers should be influenced by temperature trends in the long term, but should show little relation with short-term fluctuations (i.e. on a scale of one or two years). The other hypothesized triggers (cold-water predation advantage to endotherms, requirement for more surface basking when water is cold) depend directly on temperature regimes, and should therefore track short-term temperature changes. The hypothesis thus gives rise to the prediction that losses to endothermic predators should track long-term temperature trends in a general way, and show some response to shorter term temperature variation, but should not track either short-term or long-term trends precisely. Salmon abundance indicators show an overall negative correlation with yearly temperature indicators but the relation does not hold up in all years. This is consistent with the above prediction.

The rise in seal numbers since the early 1980s is consistent with the hypothesis' prediction (cold water leads to an increase in endothermic predators). However other factors (population rebound following cessation of hunting, response to other changes in the ecosystem) could also explain the change in seal numbers.

The rise in endothermic predators has been accompanied by a decrease in biomass of large finfish which may prey on post-smolt salmon. However, the decrease in finfish predators does not compensate for the increase in endothermic predators, because both finfish predators and salmon are ectothermic, meaning that changes in temperature do not change the balance of advantage between them. In contrast, the cooler water gives the balance of advantage to endothermic predators vis-à-vis ectothermic salmon.

The main argument against this hypothesis is that salmon returns have continued to be depressed after water temperatures recovered following the very cold period of the early 1990s. Thus some elements of the hypothesis may be valid, but it is unlikely that it is valid in its entirety.

Tests - The notion that marine-phase salmon use behavioural thermoregulation to optimize growth could be investigated through use of data loggers that record temperature, depth, and foraging activity (this could be done by temperature loggers in the stomach or by device that measure jaw openings or swimming bursts). Simultaneously collected data on temperature profiles and position of prey would assist in interpreting behavioral patterns registered by the data loggers. Observations on behaviour of salmon in aquaculture sea-cages might also shed light on the foraging strategies of marine-phase salmon.

Booth et al. (1997) reported that swimming speeds of adult salmon over 10 sec intervals do not change between 12°C and 18°C. This is unexpected given the general relation between temperature and swimming performance in fish. Escape from predators is likely to be strongly influenced by reaction time, acceleration rate, and swimming speeds during the first 1-2 seconds after a predator attack. The relation between these measures of swimming performance and temperature could be determined in laboratory condition. Temperature control of salmon susceptibility to endothermic predators could also be tested empirically by releasing salmon and seals or seabirds into large tanks or sea-pens and observing predatory behaviour and success at various temperatures.

If predation risk is related to use of the warm surface layer, this risk should be higher when the surface layer is thinner. This prediction could be tested by comparing annual marine survival with mean thickness of the surface layer.

This hypothesis largely rests on water conditions in the Newfoundland Shelf area. However, substantial numbers of post- smolts from New England, Maritime, and Quebec rivers may summer in waters south of Newfoundland (Cairns and Reddin 2000). Therefore any relation between sea survival and surface layer thickness on the Newfoundland Shelf should be stronger for Newfoundland salmon than for fish from other areas.

Cairns (2001) provides a more detailed account of some of the approaches suggested above.

Consequences if true - Salmon returns will vary with water temperatures in a relation that reflects annual temperature variations to some degree and reflects long-term temperature variations to a greater degree.

Potential for intervention - The temperature regime cannot be altered, except in the very long-term by reduction in greenhouse gas emissions. Predator numbers can be reduced but this would elicit strong opposition.

V.4.d. Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools. (D. Cairns)

Hypothesis - Marine survival, especially in Inner Bay of Fundy (IBOF) stocks, is declining in a self-fuelled spiral because there are no longer enough post-smolts to form schools, which are the main predator defence of pelagic fishes.

Background - There is no cover in the surface waters of the ocean. Fish living in this environment reduce predation risk by forming schools, and the tendency to aggregate increases with increasing predation threat (Sogard and Olla 1997, Rangeley and Kramer 1998). Schools are maintained by visual contact among members. Schools disperse at night when the fish cannot see each other, and re-form at dawn (Ryer and Olla 1998). In general, protection against predation decreases with declining school size (Krause et al. 1998).

The behaviour of post-smolt Atlantic salmon is poorly known. Salmon smolts begin forming schools immediately upon release into sea cages (F. Whoriskey, pers. comm.) Holm et al. (1992) observed schools of post-smolts in Norway, and Dutil and Coutu (1988) found that some, but not all, post-smolts caught in gillnets were clustered. These observations suggest that post-smolt salmon have a natural schooling tendency at least to some degree.

Juvenile abundance, and presumably smolt production, have declined precipitously in Inner Bay of Fundy rivers since 1984. In other North American stocks, there has been a general decline in pre-fishery abundance, but juvenile densities have remained strong in a number of major salmon rivers. This suggests that smolt production has not declined to the same extent that adult pre-fishery abundance has.

Fish can solve the problem of lack of conspecifics by joining schools of other species, provided that they are of similar size to other school members (Peuhkuri 1997). The most likely fish with which salmon could co-school in the Bay of Fundy is herring. Salmon increase in weight approximately 75-fold between smolt exodus and return as 1SW adults (see V.4.c). Annual weight increases of 2 and 3 year old herring are typically in the order of 1.2x to 2x (Wheeler et al. 1999). Salmon must therefore have feeding rates which are much greater than those of herring. It seems unlikely that salmon could maintain the feeding rates necessary to sustain their rapid growth rates while co-schooling with herring.

Density dependence - Density dependent.

Geographic scope - The effect is most likely to occur in severely-reduced stocks, including those of the Inner Bay of Fundy and of New England. It is unlikely to occur in stocks with high smolt production.

Probable change since 1984 - Increase.

Evidence - There is no direct evidence for this hypothesis. The degree to which post-smolt salmon school in the open ocean is poorly known, and the presumed anti-predator advantage of schooling has not been tested in salmon.

Given the very small smolt production of Inner Bay of Fundy rivers it seems unlikely that sufficient numbers of post-smolts could find each other to form schools. The problem is compounded because such schools would have to re-form anew each morning, after nighttime periods when fish are likely to be widely dispersed by strong tidal currents. Hence, if post-smolts do depend on schooling for predator protection in open water, it is plausible that they have lost this protection in the Inner Bay of Fundy due to severely depleted numbers. Alternately, post-smolts from Inner Bay Rivers could co-school with post-smolts from the Saint John River, whose smolt run is reduced but still sizable. For this to occur, Saint John and Inner Bay post-smolts would have to share migratory routes for at least part of the year. It is not known whether this occurs.

In general, the high densities of juvenile salmon in many rivers in recent years suggests strong smolt production, which contrasts with weak adult returns. If the increased marine mortality occurs early in the marine phase, the hypothesis would be plausible because there would be fewer fish available to form schools. However, if the mortality increase occurs late in the marine phase there would be no decrease in the number of fish available to form schools and the hypothesis would not hold. The timing of the increase in mortality between smolt exodus and 1SW return is unknown.

Tests - See Cairns (2001). Examine data sets arising from pelagic salmon studies in Canada and Europe to evaluate the aggregative tendencies of post-smolt salmon. If post-smolts actively attempt to form schools, but school size is constrained by low fish numbers, then school size should be small in early morning and increase throughout the day. Data from surveys directed at other pelagic fishes should also be examined to determine if post-smolt salmon school with other species.

Aggregative tendencies of post-smolts could be evaluated by tracking movements of post-smolts by means of telemetry. This technique would also help clarify post-smolt movement patterns, which would assist in determining whether post-smolts of various stocks have the opportunity to school together.

The anti-predation advantages of schooling could be measured experimentally by introducing post-smolts and predators into large cages. Effects of school size should be measured by measuring predation success with varying school size.

Consequences if true - For stocks with very low smolt production, populations will spiral downward to extirpation.

Potential for intervention – Massive stocking programs would increase post-smolt numbers, thereby potentially breaking the downward spiral.

V.5. Life history

V.5.a. Density-dependent effects - See IV.5.a above.

V.5.b. Increased proportion of salmon maturing at 1SW reduces egg production of returnees
See II.5.a.

V.7. Environment - physical/biological

V.7.a Altered oceanographic conditions have led to changes in migration routes (J. Ritter, P. Amiro, and E. Baum)

Hypothesis - Major changes in the oceanographic conditions of the North Atlantic have occurred since the 1980s. These conditions have altered the temporal and spatial distribution of preferred habitat for Atlantic salmon.

Background - The mechanisms underlying the migration of Atlantic salmon are not well understood. If changes in oceanographic conditions alter migration routes of salmon and there are insufficient prey or reduced habitat along these different routes, then survival of specific smolt-classes would be reduced. The mechanisms for decreased survival may be reduced condition and possibly increased predation. Reduced condition may also delay the onset of maturation, further exposing a smolt-class to additional months of marine mortality. If there is a temporal trend in these conditions and the hypothesis is true then a temporal decline in all salmon stocks utilizing the North Atlantic would have occurred.

In the 1970s and 1980s, large numbers of salmon were tagged in North America. Most returns were from North American and Greenland waters (although two tags were returned from the British Isles, Reddin 1988). In the late 1980s and early 1990s, after tagging effort had diminished substantially, tags applied to smolts in Maine and Canada were reported from the Faeroes (e.g. Anon. 1993). These new records, and the paucity of reports from the Faeroes in earlier years when tagging was more intense, suggest that there was an increase in trans-Atlantic migration in the late 1980s or early 1990s. Such an increase might lead to a higher rate of non-return of fish unable to find their way back to North American rivers. Alternately, if the trans-Atlantic migration was bi-directional, European fish might have accompanied North American fish across the Atlantic and introduced European genes to North American rivers.

Density dependence - Density independent.

Geographic scope - Would affect all salmon stocks utilizing the Northwest Atlantic.

Probable change since 1984 - Oceanic conditions in the North Atlantic since 1984 can be described as variable. Periods of colder water and shifting (southerly) currents have occurred. Conditions have warmed substantially in recent years (Colbourne 1999a, b). There is some evidence for more trans-Atlantic migration in the late 1980s-early 1990s. There has been too little tagging since the early 1990s to determine if such migrations have continued.

Evidence - While various hypotheses concerning migration routes have been explored none has taken the place of the Salmon Habitat Index (SHI), a measure of the marine habitat area for salmon, as a significant factor in the recruitment of salmon. While the SHI and spawning escapement of salmon have both increased in the late 1990s, recruitment of salmon (measured as pre-fishery abundance) is at an all time low. Little research is available on the routes used to access that habitat, particularly since the close of the commercial salmon fishery and reduction in tagging experiments.

Tests - Examine tagging records for evidence of changing migration routes, including trans-Atlantic routes.

Consequences if true - Recruitment would vary with conditions and future recruitment may be reduced, increased or remain the same.

Potential for intervention - None.

V.7.b. Reduced prey availability decreases survival (L. Marshall and D. Cairns)

Hypothesis – Salmon survival has decreased because over-fishing, oceanographic changes, or shifts in marine migration routes have reduced abundance or availability of food for salmon. Shifts in prey distribution could have led salmon to new over-wintering areas where survival is poor.

Background - Major prey species of marine-phase Atlantic salmon include capelin, lance, cod, barracudinas, lantern fish, herring, smelt, amphipods, euphausiids, shrimp, and squid (Lear 1980). Nearly all monitored fish stocks on the Newfoundland-Labrador Shelf, particularly in the north, collapsed between 1989 and 1992-1994 (Pederson and Rice 1999, Rice 1999, Zwanenburg et al. 1999). The collapses included several species of groundfish not targeted by fisheries. Groundfish collapses were accompanied by a reduction in weights-at-age and condition factors. A corresponding increase in abundances of shrimp on the Shelf and in West Greenland may not have been physically available or an appropriate equivalent to fish prey for salmon.

Density dependence - Density independent, at least at the projected levels of North American smolt production.

Geographic scope - Could affect salmon throughout their range in eastern North America.

Probable change since 1984 – The changing state of large marine ecosystems and expansion of industrial fisheries since 1984 may have reduced the prey of salmon thereby diminishing their survival.

Evidence - None. The decline in North American salmon returns has not been accompanied by a decrease in mean weights or lengths of returning 1SW and 2SW fish. In recent years, sizes at age of adult salmon returning to the Miramichi have been the largest in the 28 year time series (Chaput et al. 2000). Therefore, if marine survival has decreased because of lack of food, those fish that survive food shortages must have subsequently found sufficient food to regain "normal" weights or avoided prey shortages in the first place. The alternate hypothesis would be that only the small post-smolts destined to be 2SW salmon starved, thereby leaving the mean lengths of 1SW survivors unchanged. Because maturing 1SW salmon are many times heavier than early post-smolts, it is conceivable that starvation might kill early post-smolts, and that the survivors regain their normal growth trajectories and return to their rivers as grilse or salmon of normal weight. Experiments in Newfoundland have shown that post-smolt salmon can live 6-8 weeks without feeding (Dempson et al. 1999b), which suggests that food shortages would have to be intense and long-lasting if they are to reduce survivorship.

It is less conceivable that larger fish might suffer food shortage to the point where a significant proportion of the population starves, while the survivors fully recover their weights by the following year.

Tests - The hypothesis could be explored by examining scale or otolith growth rings to determine if starvation periods exists or if over 10-15 years, length, weight or condition factors exhibit a trending "skew" that was un-associated with closure of salmon fisheries. A collection of stomach contents of salmon at sea for comparison with previous studies might indicate if diet of survivors has changed. Radio tracking of salmon at sea would provide the potential to ascertain the ecological make-up of the occupied habitat and the relative abundance of prey (and predators).

Consequences if true - Salmon declines will continue until prey stocks recover in areas frequented by salmon during the principal marine growth phase.

Potential for intervention - If the prey decline is due to overfishing, Impose or maintain a fishing management regime that allows recovery of prey stocks.

V.7.c. UV exposure reduces survival of post-smolts

(D. Cairns and G. Chaput)

Hypothesis - Increasing exposure to radiation during freshwater rearing, estuarine passage, or marine life causes metabolic damage that results in increased mortality.

Background - Salmon swim near the surface of the ocean where UV penetration is most intense. UV radiation can have a variety of physiological effects; see Walters and Ward (1998) and IV.7.c above.

Density dependence - Density independent.

Geographic scope - May affect salmon anywhere in the marine environment.

Probable change since 1984 - UV radiation has probably increased due to the thinning of the ozone layer.

Evidence - None.

Tests - Compare growth and survivorship of salmon in sea-cages with and without overhead shade, and among years with varying cloud cover. Examine records of changes in UV intensity in the Northwest Atlantic.

Consequences if true - Marine survival rates will remain low as long as UV levels are high.

Potential for intervention - Reduce ozone-depleting activities.

V.7.d. Local decreases of ocean productivity depress returns of some stocks because salmon have fixed migration patterns that are river- or region-specific

(D. Cairns)

Hypothesis - Ocean productivity, or some other factor which affects survival of salmon, has been depressed in local areas of the northwest Atlantic. Salmon stocks migrate to these areas or pass through them at critical stages due to fixed migration patterns. These salmon suffer lower marine survival.

Background - In the northeast Pacific, coho salmon and steelhead trout that migrate to certain regions of the ocean have suffered temporally coherent loss of returns, while fish that use other marine areas show no such decreases (Welch et al. 2000, Beamish et al. 2000). For such an effect to occur, fish must have a strong disposition (presumably genetically based) to use the affected area of ocean even if conditions are not suitable there. Negative effects on survival could also occur if fish are obliged to pass through the affected area to reach more hospitable areas.

Trends in salmon return rates in the northwest Atlantic show substantial geographic variation. In general, stocks in southern areas are faring more poorly than those of northern areas, but there is also much variation at smaller geographic scales. For example, stocks in northern mainland Nova Scotia and western Cape Breton Island are in good condition, while those of areas immediately to the west (southeastern New Brunswick) and east (eastern Cape Breton Island) are doing poorly (DFO 1999a).

Tag returns suggest that postsmolt salmon from the Maritime provinces commonly summer in waters in the general area of their home rivers (Ritter 1989, Cairns and Reddin 2000). Post-smolts are thought to spend their first marine winter on the Newfoundland-Labrador Shelf, but direct evidence of this is lacking. It is widely believed that all sea-run salmon in northeastern North America migrate to the Newfoundland-Labrador Shelf area (except those of the inner Bay of Fundy, IBOF). This is supported by the wide range of river ages found in post-smolt samples there (Reddin and Short 1991). However, there is no proof that all non-IBOF fish migrate to this area.

Density dependence - None.

Geographic scope - Potentially affects salmon throughout its range in the Northwest Atlantic, but in a locally heterogeneous manner.

Probable change since 1984 - It is not known whether there are local pockets where oceanographic productivity has decreased since 1984.

Evidence - IBOF salmon are reared in rivers which appear not to be severely constrained by habitat factors. But IBOF salmon, whose sea life is confined to the Bay of Fundy - Gulf of Maine, have low return rates in comparison with stocks which are long-distance migrants. This situation is consistent with the hypothesis. For non-IBOF stocks, migration patterns are not sufficiently well known to determine whether fish have stock- or region-specific migration routes. It is thus possible that some non-IBOF stocks are obligate users of certain parts of the ocean which are poorly suited for salmon. If so, the hypothesis would be true, and would explain the geographic heterogeneity of return rates.

Tests - Re-examine tagging and other records for evidence that post-smolts have migration patterns that are specific to rivers or groups of rivers. Use additional conventional or electronic tags to clarify migration patterns. Use this information to map survival or return rates in relation to areas of ocean used. Examine physical, chemical, and biological parameters of such areas for factors which may affect salmon survival.

Consequences if true - Survival will be poor as long as unfavourable conditions persist in the affected areas.

Potential for intervention - Production enhancement by freshwater habitat improvement or by stocking fish of local origin will not improve returns, because fish will persist in migrating to ocean areas where survival is poor. Runs could be maintained or increased by stocking fish from rivers where stocks are strong due to use of favourable ocean areas.

V.8. Environment - thermal

V.8.a. Lower marine temperatures reduce survival (D. Cairns)

Hypothesis - Lower temperatures in the Northwest Atlantic have reduced marine survival of Atlantic salmon.

Background - Correlations have been reported between the area of the summer Cold Intermediate Layer on the continental shelf off Newfoundland and indices of salmon abundance (Narayanan et al. 1995) A clear mechanism for these relationships has not been proposed, but it is speculated that water temperatures influence fish movements, shifting the location of nursery areas and migration pathways.

Density dependence - Density independent.

Geographic scope - Wide, because all anadromous salmon of North American origin (except Inner Bay of Fundy stocks) appear to use the continental shelf off Newfoundland.

Probable change since 1984 - Vertically averaged temperatures at Station 27 off St. John's Newfoundland showed cold periods in the mid 1980s and early 1990s, with a record low recorded in 1991 (Colbourne 1999a). In the mid- to late 1990s, temperatures recovered to normal or above-normal levels.

Evidence - There appear to be linkages between ocean temperature and marine survival of certain European stocks of Atlantic salmon (Friedland et al. 2000). In the Northwest Atlantic, surface temperatures increased and the area of the Cold Intermediate Layer shrank in the mid 1990s at a time when salmon pre-fishery abundance continued to decline. Hence the relation between temperature and marine survival is not straightforward.

Tests - In the future, compare temperature indicators with corresponding marine survival or return rates.

Consequences if true - Marine survival and returns will increase if temperatures rise.

Potential for intervention - None, unless the temperature anomalies are due to anthropogenic global climate change.

V.8.b. Climate change will alter sea temperatures, affecting marine survival (D. Cairns)

Prediction - Temperatures in the Northwest Atlantic will decrease due to global climate change, causing a decrease in marine survival of Atlantic salmon.

Background - Global climate models project an uneven distribution of warming trends. According to models, water temperatures in the Northwest Atlantic may decline or remain the same (IPCC 1995a). However, detailed projections are not available because global models lack regional precision and no regional climate model has been constructed for the Northwest Atlantic. See also III.8.a.

Density dependence - Density independent.

Geographic scope - Wide, because all anadromous North American salmon use the Northwest Atlantic.

Evidence - There is a general negative relation between some measures of water temperature in the Northwest Atlantic and salmon abundance (Narayanan 1995). However, the mechanism behind this relation is unclear and the relation does not have predictive strength in all years.

Tests – Continue to monitor and compare salmon abundance and indicators of Northwest Atlantic water temperatures in future years.

Consequences if true - Salmon returns will continue to decline if water temperatures decrease.

Potential for intervention - Decrease in greenhouse gas emissions could ease global climate changes in the very long term.

VI. ADULT RETURN THROUGH ESTUARIES

VI.2. Aquaculture

VI.2.a. Presence of salmon in sea-cages disorients returning fish (P. Amiro)

Hypothesis – I) The presence of salmon in sea cages along the return routes of salmon may disorient returning wild salmon, lessening their chances of finding and entering their home river.

Density dependence - Unknown.

Geographic scope – Limited to areas with sea-cage aquaculture. The main area is southwestern New Brunswick and eastern Maine. Smaller aquaculture operations are located at the Aspoteghan Peninsula, St. Margarets Bay, Bay d'Espoir, Bras d'Or Lakes, and Point Aconie.

Probable change since 1984 - Sea-cage culture operations, and therefore the potential to attract and disorient returning wild fish, have increased substantially since 1984 (DFO 1999b).

Evidence - Returning adult salmon from rivers of the outer and inner Bay of Fundy were intercepted in former salmon fisheries in the Fundy Isles area. This suggests that at least some salmon destined for Bay of Fundy rivers pass close to the concentration of aquaculture sites in South-west New Brunswick/Eastern Maine. Return rates of wild salmon to Fundy rivers, especially those of the inner Bay, have become consistently low since 1990.

Tests - Behaviour of adult salmon passing through waters containing sea-cages needs to be examined. The most likely technique for doing so would be acoustic telemetry.

Consequences if true - Runs of salmon in rivers close to sea-cages, and runs of salmon whose marine migrations take them close to sea-cages, will continue to diminish.

Potential for intervention - Sea-cages could be reduced in areas where their presence disorients wild fish. Convention net-cages could be replaced with impermeable bags which retain metabolites and waste products. This would reduce attraction to wild salmon.

VI.2.b. Captive and escaped aquaculture salmon transmit diseases to returning wild fish (P. Amiro)

Hypothesis - Wild salmon returning to their natal rivers acquire infections from salmon in sea-cages or from escaped salmon. Disease transmission from escaped salmon could occur close to natal rivers, or in distant waters if aquaculture escapees migrate long distances.

Density dependence - Unknown but likely density dependent.

Geographic scope – Most likely to occur in areas of salmon aquaculture. Could also occur anywhere in the northwest Atlantic if aquaculture escapees undergo long-distance migrations.

Probable change since 1984 - Salmon aquaculture has increased substantially between 1984 and 1999. During this period there have been major outbreaks of disease and parasites in salmon aquaculture (DFO 1999b).

Evidence - Circumstantial. Ectoparasite numbers have been noted to be higher in salmon stocks returning proximate to sea farming operations. All sea-farming associated diseases have now been detected in wild salmon but there is no evidence that they have impacted wild populations. Some argue that all diseases are of wild origin.

Tests - Few conclusive tests are available to test exposure to unique salmon farming pathogens and sampling rates required are higher than those available or tolerable in many wild stocks close to salmon farms.

Consequences if true - Salmon populations which acquire disease from aquaculture fish will continue to suffer mortality from this source.

Potential for intervention - Better disease control in aquaculture fish, containment of organisms, associated biologics and chemicals resulting from cultivation of salmon. Containment could be achieved by replacing net-cages with impermeable bags.

VI.4. Predation

VI.4.a. Seal predation in estuaries reduces survival of returning adults (D. Cairns)

Hypothesis - Seal predation on adults returning through estuaries depresses North American Atlantic salmon returns.

Background - 1SW and MSW salmon are too large for seabirds and other fish (except sharks) to attack. Hence seals are the major potential predator of salmon in estuaries.

Density dependence - Density dependent or density independent. If the salmon run is large, it is possible that seals may be attracted. This could lead to a higher exploitation rate due to increased number of predators, or a lower predation rate due to protection conferred by schooling behaviour.

Geographic scope - Seals may be present in estuaries throughout the North American range of Atlantic salmon. Reports of seal-salmon interactions in estuaries are most common in New England and in Labrador, but this may be due to greater attention being paid to the issue in those areas.

Probable change since 1984 - Increase.

Evidence - Seal numbers in estuaries appear to have increased since the 1980s, at least in some areas (see IV.4.a). DFO biologists and enforcement officers have reported sightings of seals pursuing and eating salmon in estuaries in Newfoundland and Labrador (Cairns and Reddin 2000). Salmon that survive seal attacks may bear scars that are recorded at counting stations in rivers. The proportion of salmon reported to be scarred has risen in Maine rivers, but it is uncertain whether this is due to better reporting by field staff (Baum 1997).

Tests - This hypothesis could be directly tested using the methods of IV.4.a (above). However, large sample sizes would probably be required for reliable conclusions. The rate of seal-induced scarring on returning salmon may indicate the frequency of seal attacks. Long-term records of salmon returning to Mactaquac on the Saint John River could be used to evaluate trends in seal attack rates on salmon returning to that system. A negative correlation between scarring rates and sea survival would lend support to the hypothesis.

Consequences if true - Salmon returns will continue to decline unless predator numbers fall.

Potential for intervention - Predation pressure could be reduced by predator culls or increased predator harvests. However, such programs would encounter strong opposition.

VI.4.b Aquaculture sites attract predators, thereby increasing predation on returning adults (D. Cairns and D. Meerburg)

Hypothesis - Predators, especially seals, are attracted to aquaculture sites. Returning adults heading for nearby rivers suffer increased predation mortality because they must pass through this predation field.

Background - Salmon confined to sea cages offer a concentrated food supply which may attract seals to aquaculture sites. On the other hand, seals may be discouraged from attending aquaculture areas by harassment and shooting. See also IV.4.c.

Density dependence - Density independent.

Geographic scope - Coastal areas where sea-cages are located.

Probable change since 1984 - Possible increase with expansion of salmon aquaculture industry.

Evidence - Surveys conducted in 1984, 1987, and 1998 showed no evidence that seals in the Bay of Fundy area are attracted to aquaculture sites (Jacobs and Terhune 2000). See IV.4.c for additional points.

Tests - Obtain information on seal numbers at cage sites from aquaculture operators. Evaluate seal predation patterns by examining adults returning through aquaculture areas for seal-induced scars.

Consequences if true - Sea survivorship of salmon whose natal rivers exit near aquaculture sites will continue to be low.

Potential for intervention - Reducing the vulnerability of sea-cages to seal attacks will reduce their attractiveness to seals. Eliminate seals which visit aquaculture areas.

VI.6. Environment - chemical

VI.6.a. Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river (G. Chaput)

Hypothesis - Adults migrating through estuaries are negatively impacted by pollution and chemicals.

Background - Potential problems are similar to those faced by out-going smolts; see IV.6.a.

Density dependence - Density independent.

Geographic scope - Throughout the salmon's range, but most likely to occur in southern areas which are more industrialized.

Probable change since 1984 - Reductions of industrial activities and improvements in effluent treatments should have improved the situation.

Evidence - State of the environment reports by Environment Canada and ongoing monitoring programs.

Tests - Trials to measure survivorship and egg/milt viability after exposure to estuarine waters.

Consequences if true - Deleterious estuarine conditions may aggravate already low at-sea survivals of salmon. Recovery of salmon stocks may be delayed or hampered.

Potential for intervention - Effluent discharge can be reduced.

Sources - See IV.6.a.

PLAUSIBILITY ANALYIS

Factors hypothesized to have contributed to the decline in pre-fishery abundance, and predictions of climate change projections, are listed in Table 1. This table classifies each factor according to whether its effects are density dependent, proportion of the factor that is due to human activities, and the potential for intervention to reduce or reverse negative effects.

Area, Degree, Magnitude, and Trend scores for each district are presented numerically in Tables 2-5 and graphically in Table 6. Mean, SD, minimum, and maximum for Magnitude, Trend, and the product of Magnitude and Trend are presented for each factor in Table 7. Table 8 orders factors operating in freshwater (adult to egg, egg to hatch, hatch to smolt) by Magnitude x Trend, based on mean scores weighted by egg conservation requirement.

The highest ranking factor in the freshwater phases was reduced juvenile survival due to inter- and intra-specific competition. This factor ranked seventh in the overall rankings. The next highest ranking factors in freshwater were reduced reproductive output because grilse are an increasing fraction of returnees, limitation of juvenile production by high summer temperatures, and reduced spawning success due to wild-aquaculture crosses (Table 8).

In estuarine phases (smolt passage, adult return), the factor with the highest weighted Magnitude x Trend score was reduced smolt survival due to fish predation (Table 9). This factor was second in the overall rankings. The next most strongly ranked factors in estuarine phases were reduced smolt survival due to bird and seal predation, reduced survival at sea due to density-dependent effects in freshwater, and reduced survival of returning adults due to seal predation in estuaries.

Three of the four highest factors in overall rankings were in the marine phase. The highest marine rank, and the highest overall rank, was occupied by the hypothesis that post-fishery marine mortality is higher than what is presumed by fisheries models. This is not a mortality factor as such but reflects the likelihood that natural mortality in the marine phase is probably not constant, probably higher than that used in prefishery abundance models, and may have increased over the last two decades. Increases in natural mortality could have resulted from many of the factors identified in this document.

The highest ranking marine factors that could directly cause mortality were bird and mammal predation (rank 3 overall) and changes in migration routes due to altered oceanographic conditions (rank 4 overall).

DISCUSSION

The decline of salmon pre-fishery abundance in the northwest Atlantic has been a source of concern for several years, and possible causes have been discussed in numerous papers (e.g. Dempson et al. 1998, Anon. 2000, Potter and Crozier 2000, Reddin et al. 2000). Declines in European Atlantic salmon and in Pacific salmon have raised similar concerns (Anon. 2000, Brodeur et al. 2000).

This document differs from others that address salmon declines because it attempts to catalogue all potential causes with any reasonable claim to credibility. This approach emphasizes breadth of coverage rather than depth of treatment. Accounts for hypothesized factors summarize the main points pertaining to each factor, and direct readers to key papers that treat the factor in fuller detail.

The present paper also differs from previous reviews because it provides a systematic assessment of the plausibility of each hypothesized factor. This offers researchers a semi-quantitative means of determining which factors have the greatest likelihood of having contributed to the decline, and which, therefore, are the most worthy of further research.

We have rated and ranked the plausibility of each hypothesized factor by assigning Area, Degree, and Trend scores for each district. In theory, this process could be based on direct field data. For example, the Trend score could be the Pearson correlation coefficient between numbers of salmon returning to district rivers and a quantitative measure of the hypothesized factor for 1986-1999. In practice, the hard data required for such an exercise are almost never available. Since a strictly quantitative scoring is not possible, we have relied on subjective evaluations by salmon biologists with local knowledge. The process of scoring factors that operate in freshwater is probably reasonably reliable. The scoring of estuarine and marine factors is less reliable, because marine mortality processes are poorly understood, and because trends in intensity of marine factors are often poorly known.

The plausibility analysis in this paper applies to salmon spawning in Quebec, the Maritime Provinces, and New England. Plausibility scores are unavailable for Newfoundland and Labrador rivers, which received a mean of 51% of the salmon that returned to North American rivers in 1984-1997 (Anon. 2000).

Because of these limitations, our ratings must be considered only as rough guides to the plausibility of hypothesized factors. A factor with a low Magnitude score and a negative Trend score has little chance of explaining the salmon decline, but any factor with a strong Magnitude score and a positive Trend score is a plausible candidate to explain the decline.

An additional limitation to this analysis is its treatment of individual factors as separate and independent. It is very improbable that the salmon decline is due to a single cause, and factors contributing to the decline are likely to have acted in a cumulative or synergistic manner. Thus it is possible that two or several factors with moderate or low rankings could be acting together to produce a major effect.

The summation of scores across districts emphasizes the identification of widespread causes of the decline in pre-fishery abundance. However, factors that constrain salmon survival and reproduction often vary regionally. The district plausibility scores (Tables 2-5) may aid identification of local constraints to salmon survival and reproduction, especially in freshwater.

Consistent with the widely held view that the decline of Atlantic salmon pre-fishery abundance is due to low survival at sea (Hawkins 2000), 10 of the 12 top-ranked hypothesized factors impact salmon in the estuarine or marine environment (Tables 8-10). However, one of these, the hypothesis that density-dependent effects at the juvenile stage reduce marine survival, is based on a cause that occurs in fresh water. Of these 12 top-ranked factors, five are related to predation, five are related to life history, one is related to fisheries, and one is related to the physical/biological environment.

The hypothesis that ranks first overall is that the reduction in pre-fishery abundance has been overestimated because the natural mortality used in PFA models is erroneously high. This hypothesis is unlike all others because it deals with a method of analysis rather than a phenomenon of the real world. If this hypothesis is true, then the decline of salmon pre-fishery abundance would be, at least in part, an artifact of calculation. Given the dramatic changes of the last two decades in the physical and biological environment inhabited by marine-phase Atlantic salmon, it is likely that natural mortality has increased, and may well be substantially higher than that assumed in PFA models.

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Table 1

Density dependence, proportion of factor that is due to human activities, and potential for intervention for factors hypothesized to reduce reproduction or survival of North American populations of Atlantic salmon.

Hypothesized factor	Density dependence[a]	Proportion of factor that is due to human activities	Potential for intervention to reduce or reverse negative effects
I. Returning adult to egg			
1. Fisheries			
a Fishery removals in estuaries and rivers	DI	All	High
b Hook-and-release mortality	DI	All	High
2. Aquaculture			
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	DI	All	High
b Aquaculture escapees compete with wild fish for spawning sites	DD	All	High
c Hatchery-reared salmon have lower spawning success than wild salmon	DI	All	High
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	DI	All	High
3. Disease			
a Naturally-occurring disease	DD	None	Low
b Disease transmitted from captive or escaped aquaculture fish	DD	All	High
4. Predation			
5. Life history			
6. Environment - chemical			
7. Environment - physical/biological			
a Barriers to spawning migration	DI	Most	High
b Spawning habitat is limited	DD	Some	Some
c Alterations to discharge patterns reduce access to spawning areas	DI	All	High
8. Environment - thermal			
a High water temperatures delay access to spawning grounds	DI	Some	Some
II. Egg to hatch			
1. Fisheries			
2. Aquaculture			
a Eggs from wild-aquaculture crosses have reduced viability	DI	All	High
3. Disease			
a Disease and parasitism reduce egg survival	DD	Some	Some
4. Predation			
a Predation reduces egg survival	DD	None	None
5. Life history			
a Reproductive output is reduced because grilse are an increasing fraction of returnees	DI	Some	High
6. Environment - chemical			
a Low pH due to acid precipitation reduces egg survival	DI	All	Some
7. Environment - physical/biological			
a Sedimentation processes reduce egg survival	DI	Most	High
b Alteration of discharge patterns reduces egg survival	DI	None	None
8. Environment - thermal			
III. Hatch to smolt			
1. Fisheries			
2. Aquaculture			
a Competition with aquaculture escapees reduces juvenile survival	DD	All	High
3. Disease			
a Disease and parasitism reduce juvenile survival	DD	Some	Low
4. Predation			
a Avian predators reduce juvenile survival	DD, DI	None	Some
5. Life history			
a Precocious maturation reduces the number of juveniles which will become smolts	?	None	None
b Inter- and intra-specific competition reduces juvenile survival	DD	None	High
6. Environment - chemical			
a Toxic chemicals reduce juvenile survival	DI	All	All
b Low pH due to acid precipitation reduces juvenile survival	DI	All	Some
7. Environment - physical/biological			
a Sedimentation processes reduce juvenile survival	DI	Most	High
b Alterations to discharge patterns reduce juvenile survival	DI	Some	Some
8. Environment - thermal			
a High summer temperatures reduce juvenile production	DI	Some	Some
b Limited availability of thermal refugia reduces juvenile survival	DD, DI	Some	Some

Table 1 (continued)

Hypothesized factor	Density dependence[a]	Proportion of factor that is due to human activities	Potential for intervention to reduce or reverse negative effects
IV. Smolt passage through rivers and estuaries			
1. Fisheries			
2. Aquaculture			
a Aquaculture escapees increase competition for resources in the estuary	DD	All	High
3. Disease			
4. Predation			
a Bird and seal predation reduces survival of smolts in rivers and estuaries	DI	None	Some
b Fish predation reduces survival of smolts in rivers and estuaries	DD	None	Some
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	DI	All	High
5. Life history			
a Density-dependent effects in freshwater affect subsequent survival at sea	DD	None	High
6. Environment - chemical			
a Toxic chemicals affect smolt migration and reduce survival	DI	All	Some
b Discharges of steroidogenic compounds compromise the parr-smolt	DI	All	High
c Low pH of rivers decreases survival of descending smolts	DI	All	Some
7. Environment - physical/biological			
a Dams reduce the number of smolts reaching the estuary	DI	All	Some
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	DI	All	High
c UV exposure in fresh water or in estuaries reduces survival of smolts	DI	All	Some
8. Environment - thermal			
a Alterations in spring temperature regimes increase smolt mortality	DI	Some	Some
V. Ocean life			
1. Fisheries			
a Commercial fisheries in Greenland harvest more salmon than is officially reported	DI	All	High
b Undocumented commercial fisheries reduce marine survival	DI	All	Some
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	DI	None	None
2. Aquaculture			
a Aquaculture escapees compete with wild salmon for resources in the ocean	DD	All	High
3. Disease			
a Disease and parasites reduce sea survival	DI	None	None
4. Predation			
a Predation by other fish reduces marine survival	DD	None	None
b Predation by birds and marine mammals reduces marine survival	DI	None	Some
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	DI	None	Some
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation.	DD	None	Some
5. Life history			
a Density-dependent effects in freshwater affect subsequent survival at sea	DD	None	High
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	DI	None	None
6. Environment - chemical			
7. Environment - physical/biological			
a Altered oceanographic conditions have lead to changes in migration routes	DI	None	None
b Reduced prey availability decreases survival	DI	None	None
c UV exposure reduces survival of post-smolts	DI	All	Some
d Local decreases of ocean productivity depress returns of some stocks because salmon have fixed migration patterns that are region-specific.	DI	None	Some
8. Environment - thermal			
a Lower marine temperatures reduce survival	DI	None	None

Table 1 (continued)

Hypothesized factor	Density dependence[a]	Proportion of factor that is due to human activities	Potential for intervention to reduce or reverse negative effects
VI. Adult return through estuaries			
1. Fisheries			
2. Aquaculture			
a Presence of salmon in sea-cages disorients returning fish	?	All	High
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	DD	All	High
3. Disease			
4. Predation			
a Seal predation in estuaries reduces survival of returning adults	DD, DI	None	High
b Aquaculture sites attract predators, thereby increasing predation on returning adults	DI	All	High
5. Life history			
6. Environment - chemical			
a Pollution in estuaries reduces survival of returning adults or lowers their ability to	DI	All	High
7. Environment - physical/biological			
8. Environment - thermal			

[a] DD - density dependent, DI - density independent

Table 2

Factors hypothesized to reduce reproduction or survival of North American populations of Atlantic salmon, and their estimated plausibility by district in Quebec.

Hypothesized factor	Q11, Ungava Bay Ungava Bay				Q8, Q9; N. Shore, Gulf of St. Lawrence				Q5, Q6, Q7; N. Shore, St. Lawrence estuary				Q1,Q2,Q3,Q10; S.Shore, St. Law. est, Gaspé Pen, Anticosti I			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
I. Returning adult to egg																
1. Fisheries																
a Fishery removals in estuaries and rivers	1.0	0.5	0.50	-0.2	1.0	0.5	0.50	-0.3	1	0.5	0.50	0	1	0.5	0.50	-0.1
b Hook-and-release mortality	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.1	1	0.1	0.10	0.2	1	0.1	0.10	0.5
2. Aquaculture																
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
b Aquaculture escapees compete with wild fish for spawning sites	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
c Hatchery-reared salmon have lower spawning success than wild salmon	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Naturally-occurring disease	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	-0.2	1	0.1	0.10	-0.2
b Disease transmitted from captive or escaped aquaculture fish	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	1	0.1	0.10	-0.1	1	0.1	0.10	-0.1
7. Environment - physical/biological																
a Barriers to spawning migration	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5
b Spawning habitat is limited	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
c Alterations to discharge patterns reduce access to spawning areas	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
8. Environment - thermal																
a High water temperatures delay access to spawning grounds	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.5	0.1	0.05	-0.2	0.5	0.1	0.05	-0.2
II. Egg to hatch																
2. Aquaculture																
a Eggs from wild-aquaculture crosses have reduced viability	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Disease and parasitism reduce egg survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
4. Predation																
a Predation reduces egg survival	1.0	0.5	0.50	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	-0.2
5. Life history																
a Reproductive output is reduced because grilse are an increasing fraction of returnees	1.0	0.3	0.30	-0.5	1.0	0.1	0.10	0.4	1	0.1	0.10	0.4	1	0.1	0.10	0.4
6. Environment - chemical																
a Low pH due to acid precipitation reduces egg survival	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	0	0	0.00	0
7. Environment - physical/biological																
a Sedimentation processes reduce egg survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.4	0.4	0.16	0.2	0.4	0.4	0.16	0.2
b Alteration of discharge patterns reduces egg survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.1	0.2	0.02	0	0.1	0.2	0.02	0
III. Hatch to smolt																
2. Aquaculture																
a Competition with aquaculture escapees reduces juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Disease and parasitism reduce juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
4. Predation																
a Avian predators reduce juvenile survival	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.2	1	0.1	0.10	0.2	1	0.1	0.10	0.2
5. Life history																
a Precocious maturation reduces the number of juveniles which will become smolts	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	0
b Inter- and intra-specific competition reduces juvenile survival	1.0	0.5	0.50	-0.5	1.0	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.2	0.20	0.5
6. Environment - chemical																
a Toxic chemicals reduce juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
b Low pH due to acid precipitation reduces juvenile survival	0.1	0.5	0.05	0.0	0.1	0.5	0.05	0.0	0.1	0.5	0.05	0	0	0	0.00	0
7. Environment - physical/biological																
a Sedimentation processes reduce juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.4	0.2	0.08	0.2	0.4	0.2	0.08	0.2
b Alterations to discharge patterns reduce juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
8. Environment - thermal																
a High summer temperatures reduce juvenile production	0.0	0.0	0.00	0.2	0.0	0.0	0.00	0.2	0.5	0.3	0.15	0.2	0.5	0.3	0.15	0.2
b Limited availability of thermal refugia reduces juvenile survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0.3	0.2	0.06	0.1	0.3	0.2	0.06	0.1

Table 2 (continued)

Hypothesized factor	Q11, Ungava Bay Ungava Bay				Q8, Q9; N. Shore, Gulf of St. Lawrence				Q5, Q6, Q7; N. Shore, St. Lawrence estuary				Q1,Q2,Q3,Q10; S.Shore, St Law est, Gaspé Pen, Anticosti I			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
IV. Smolt passage through rivers and estuaries																
2. Aquaculture																
a Aquaculture escapees increase competition for resources in the estuary	0.0	0.0	0.00	0.5	0.0	0.0	0.00	0.5	0	0	0.00	0.5	0	0	0.00	0.5
4. Predation																
a Bird and seal predation reduces survival of smolts in rivers and estuaries	1.0	0.5	0.50	0.3	1.0	0.5	0.50	0.3	1	0.5	0.50	0.3	1	0.5	0.50	0.3
b Fish predation reduces survival of smolts in rivers and estuaries	1.0	0.2	0.20	0.0	1.0	0.2	0.20	0.1	1	0.2	0.20	0.1	1	0.2	0.20	0.1
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
5. Life history																
a Density-dependent effects in freshwater effect subsequent survival at sea	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	0
6. Environment - chemical																
a Toxic chemicals affect smolt migration and reduce survival	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	1	0.1	0.10	0	1	0.1	0.10	0
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	1	0.1	0.10	0	1	0.1	0.10	0
c Low pH of rivers decreases survival of descending smolts	0.1	0.1	0.01	0.0	1.0	0.3	0.30	0.0	1	0.1	0.10	0	0	0	0.00	0
7. Environment - physical/biological																
a Dams reduce the number of smolts reaching the estuary	0.0	0.0	0.00	0.0	0.1	0.2	0.02	0.0	0.1	0.2	0.02	0.2	0.1	0.2	0.02	0.2
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	0.0	0.0	0.00	0.0	0.1	0.1	0.01	0.0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
c UV exposure in fresh water or in estuaries reduces survival of smolts	1.0	0.1	0.10	0.2	0.8	0.1	0.08	0.2	0.8	0.1	0.08	0.2	0.8	0.1	0.08	0.2
8. Environment - thermal																
a Alterations in spring temperature regimes increase smolt mortality	1.0	0.1	0.10	-0.4	1.0	0.1	0.10	-0.4	1	0.1	0.10	-0.4	1	0.1	0.10	-0.4
V. Ocean life																
1. Fisheries																
a Commercial fisheries in Greenland harvest more salmon than is officially reported	1.0	0.2	0.20	0.2	1.0	0.2	0.20	0.2	1	0.2	0.20	0.2	1	0.2	0.20	0.2
b Undocumented commercial fisheries reduce marine survival	1.0	0.1	0.10	-0.2	1.0	0.1	0.10	-0.2	1	0.1	0.10	-0.2	1	0.1	0.10	-0.2
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	1.0	0.5	0.50	0.0	1.0	0.5	0.50	0.0	1	0.5	0.50	0	1	0.5	0.50	0
2. Aquaculture																
a Aquaculture escapees compete with wild salmon for resources in the ocean	0.0	0.0	0.00	0.1	0.1	0.1	0.01	0.1	0.1	0.1	0.01	0.1	0.1	0.1	0.01	0.1
3. Disease																
a Disease and parasites reduce sea survival	0.0	0.0	0.00	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	0
4. Predation																
a Predation by other fish reduces marine survival	1.0	0.2	0.20	-0.1	1.0	0.2	0.20	-0.1	1	0.2	0.20	-0.1	1	0.2	0.20	-0.1
b Predation by birds and marine mammals reduces marine survival	1.0	0.5	0.50	0.5	1.0	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.5	0.50	0.5
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	1.0	0.4	0.40	0.4	1.0	0.4	0.40	0.4	1	0.4	0.40	0.4	1	0.4	0.40	0.4
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation.	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	0
5. Life history																
a Density-dependent effects in freshwater affect subsequent survival at sea	1.0	0.1	0.10	0.1	1.0	0.1	0.10	0.1	1	0.1	0.10	0.1	1	0.1	0.10	0.1
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	1.0	0.2	0.20	0.5	1.0	0.2	0.20	0.4	1	0.2	0.20	0.4	1	0.2	0.20	0.4
7. Environment - physical/biological																
a Altered oceanographic conditions have led to changes in migration routes	1.0	0.1	0.10	0.1	1.0	0.1	0.10	0.1	1	0.1	0.10	0.1	1	0.1	0.10	0.1
b Reduced prey availability decreases survival	1.0	0.1	0.10	0.0	1.0	0.1	0.10	0.0	1	0.1	0.10	0	1	0.1	0.10	0
c UV exposure reduces survival of post-smolts	1.0	0.1	0.10	0.1	1.0	0.1	0.10	0.1	1	0.1	0.10	0.1	1	0.1	0.10	0.1
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1
8. Environment - thermal																
a Lower marine temperatures reduce survival	1.0	0.3	0.30	0.3	1.0	0.3	0.30	0.3	1	0.3	0.30	0.3	1	0.3	0.30	0.3

Table 2 (continued)

Hypothesized factor	Q11, Ungava Bay Ungava Bay				Q8, Q9; N. Shore, Gulf of St. Lawrence				Q5, Q6, Q7; N. Shore, St. Lawrence estuary				Q1,Q2,Q3,Q10; S.Shore, St. Law. est, Gaspé Pen, Anticosti I			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
VI. Adult return through estuaries																
2. Aquaculture																
a Presence of salmon in sea-cages disorients returning fish	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0	0	0	0.00	0
4. Predation																
a Seal predation in estuaries reduces survival of returning adults	1.0	0.2	0.20	0.5	1.0	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.2	0.20	0.5
b Aquaculture sites attract predators, thereby increasing predation on returning adults	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	0	0	0.00	0.2	0	0	0.00	0.2
6. Environment - chemical																
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	0.0	0.0	0.00	0.0	0.0	0.0	0.00	0.0	1	0.5	0.50	0	1	0.5	0.50	0
Plausibility ratings by	G. Ouellet				F. Caron				F. Caron				F. Caron			
Egg requirement for conservation, millions[e]					15.2				46.4				46.4			
Weighting factor[f]	1.00				0.29				0.89				0.89			

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[a] Proportion of salmon habitat within the region that is affected by the hypothesized factor

[b] Degree to which the hypothesized factor constrains survival or reproductive output. 0 - no effect, 0.1 - minor effect, 0.2 - small effect, 0.5 - significant effect, 0.8 - major effect, 1.0 - drastic effect

[c] Magnitude of the effect, calculated as Proportion of habitat affected x Degree to which the factor constrains survival or reproductive output

[d] Positive numbers indicate that the factor has intensified since 1984, causing increasing mortality or constraint on reproductive output. Negative numbers mean the opposite. 1 and -1 mean a large change in intensity and 0.5 and -0.5 mean a moderate change. 0 means no change in intensity since 1984.

[e] From O'Connell et al. 1997

[f] Weighting factor = Egg requirement for conservation/mean egg requirement for conservation. Weighting factor = 1 when egg requirements for conservation is unavailable.

Table 3

Factors hypothesized to reduce reproduction or survival of North American populations of Atlantic salmon, and their estimated plausibility by region by Salmon Fishing Area in the southern Gulf of St. Lawrence^e.

Hypothesized factor	SFA 15				SFA 16				SFA 17				SFA 18			
	Northern New Brunswick				Eastern New Brunswick				Prince Edward Island				Gulf Nova Scotia			
	Area^a	Degree^b	Mag ^{c}	Trend^d	Area^a	Degree^b	Mag. ^{c}	Trend^d	Area^a	Degree^b	Mag ^{c}	Trend^d	Area^a	Degree^b	Mag ^{c}	Trend^d
I. Returning adult to egg																
1. Fisheries																
a Fishery removals in estuaries and rivers	1	0.5	0.50	0	1	0.5	0.50	0	1	0.1	0.10	-0.2	1	0.1	0.10	0
b Hook-and-release mortality	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.1	0.10	0.4	1	0	0.00	0
2. Aquaculture																
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
b Aquaculture escapees compete with wild fish for spawning sites	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
c Hatchery-reared salmon have lower spawning success than wild salmon	0.1	0.1	0.01	0	0.1	0.1	0.01	0	1	0.1	0.10	0	0	0	0.00	0
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Naturally-occurring disease	0.9	0.5	0.45	0	0.8	0.1	0.08	0.2	1	0.1	0.10	0	1	0.2	0.20	0.5
b Disease transmitted from captive or escaped aquaculture fish	0	0	0.00	0	0	0	0.00	0	1	0	0.00	0	0.1	0.1	0.01	0.5
7. Environment - physical/biological																
a Barriers to spawning migration	0	0	0.00	0	0	0	0.00	0	0.3	1	0.30	0	0	0	0.00	0
b Spawning habitat is limited	1	0.2	0.20	0	1	0.2	0.20	0	0.9	0.6	0.54	0.5	0.1	0.1	0.01	0
c Alterations to discharge patterns reduce access to spawning areas	1	0.1	0.10	0	1	0.1	0.10	0	1	0	0.00	0	0	0	0.00	0
8. Environment - thermal																
a High water temperatures delay access to spawning grounds	0.5	0.1	0.05	0	0.5	0.1	0.05	0.1	1	0	0.00	0	1	0.2	0.20	0.5
II. Egg to hatch																
2. Aquaculture																
a Eggs from wild-aquaculture crosses have reduced viability	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Disease and parasitism reduce egg survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0
4. Predation																
a Predation reduces egg survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0
5. Life history																
a Reproductive output is reduced because grilse are an increasing fraction of returnees	1	0.1	0.10	0	1	0.1	0.10	0	1	0.2	0.20	0	1	0	0.00	0
6. Environment - chemical																
a Low pH due to acid precipitation reduces egg survival	0	0	0.00	0	0.2	0.1	0.02	0	0	0	0.00	0	0	0	0.00	0
7. Environment - physical/biological																
a Sedimentation processes reduce egg survival	1	0.2	0.20	0	1	0.2	0.20	0	1	0.8	0.80	0.5	0.2	0.2	0.04	0.5
b Alteration of discharge patterns reduces egg survival	0.1	0.2	0.02	0.5	0.1	0.2	0.02	0.5	0	0	0.00	0	0.2	0.2	0.04	0.5
III. Hatch to smolt																
2. Aquaculture																
a Competition with aquaculture escapees reduces juvenile survival	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																
a Disease and parasitism reduce juvenile survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0
4. Predation																
a Avian predators reduce juvenile survival	1	0.2	0.20	0	1	0.2	0.20	0	1	0.1	0.10	0	1	0.2	0.20	0
5. Life history																
a Precocious maturation reduces the number of juveniles which will become smolts	1	0.2	0.20	0	1	0.2	0.20	0	1	0.1	0.10	0	1	0.2	0.20	0
b Inter- and intra-specific competition reduces juvenile survival	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.1	0.10	0	0.3	0.2	0.06	0.5
6. Environment - chemical																
a Toxic chemicals reduce juvenile survival	0	0	0.00	0	0	0	0.00	0	0.1	1	0.10	0.3	0	0	0.00	0
b Low pH due to acid precipitation reduces juvenile survival	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
7. Environment - physical/biological																
a Sedimentation processes reduce juvenile survival	1	0.2	0.20	1	1	0.2	0.20	0.2	1	0.5	0.50	0.5	0.2	0.2	0.04	0.5
b Alterations to discharge patterns reduce juvenile survival	1	0.2	0.20	0.1	1	0.2	0.20	0.1	0	0	0.00	0	0.2	0.2	0.04	0.5
8. Environment - thermal																
a High summer temperatures reduce juvenile production	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5	0.3	0.3	0.09	0.2	1	0.2	0.20	0.5
b Limited availability of thermal refugia reduces juvenile survival	0.5	0.2	0.10	0.1	0.5	0.2	0.10	0.2	0.3	0.3	0.09	0	1	0.2	0.20	0.5

Table 3 (continued)

Hypothesized factor	SFA 15 Northern New Brunswick				SFA 16 Eastern New Brunswick				SFA 17 Prince Edward Island				SFA 18 Gulf Nova Scotia			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
IV. Smolt passage through rivers and estuaries																
2. Aquaculture																
a Aquaculture escapees increase competition for resources in the estuary	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5
4. Predation																
a Bird and seal predation reduces survival of smolts in rivers and estuaries	1	0.2	0.20	0.1	1	0.2	0.20	0.2	1	0.1	0.10	0.2	0.2	0.1	0.02	0.5
b Fish predation reduces survival of smolts in rivers and estuaries	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	-0.2	0.2	0.1	0.02	0
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5
5. Life history																
a Density-dependent effects in freshwater affect subsequent survival at sea	1	0.5	0.50	0.5	1	0.5	0.50	0.5	0	0	0.00	0	0.3	0.2	0.06	0.5
6. Environment - chemical																
a Toxic chemicals affect smolt migration and reduce survival	0.9	0.2	0.18	0	0.9	0.2	0.18	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	0.9	0.2	0.18	0.1	0.9	0.2	0.18	0.1	0.1	0.1	0.01	0	0.2	0.1	0.02	0
c Low pH of rivers decreases survival of descending smolts	0.1	0.2	0.02	0	0.1	0.2	0.02	0	0	0	0.00	0	0	0	0.00	0
7. Environment - physical/biological																
a Dams reduce the number of smolts reaching the estuary	0	0	0.00	0	0	0	0.00	0	0.3	0.4	0.12	0	0.1	0.9	0.09	0
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	1	0.1	0.10	0	1	0.1	0.10	0	0	0	0.00	0	0.1	0.1	0.01	0
c UV exposure in fresh water or in estuaries reduces survival of smolts	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.1	0.10	0	1	0.1	0.10	0.5
8. Environment - thermal																
a Alterations in spring temperature regimes increase smolt mortality	1	0.2	0.20	0.2	1	0.2	0.20	0.2	0	0	0.00	0	1	0.1	0.10	0.5
V. Ocean life																
1. Fisheries																
a Commercial fisheries in Greenland harvest more salmon than is officially reported	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	0.7	0.1	0.07	-0.5
b Undocumented commercial fisheries reduce marine survival	1	0.2	0.20	0	1	0.2	0.20	0.2	1	0.1	0.10	-0.2	1	0.2	0.20	0
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.2	0.20	0	1	0.5	0.50	0.5
2. Aquaculture																
a Aquaculture escapees compete with wild salmon for resources in the ocean	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5
3. Disease																
a Disease and parasites reduce sea survival	1	0.2	0.20	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0
4. Predation																
a Predation by other fish reduces marine survival	1	0.2	0.20	0	1	0.2	0.20	0	1	0.2	0.20	-0.5	1	0.2	0.20	-0.5
b Predation by birds and marine mammals reduces marine survival	1	0.5	0.50	0.5	1	0.5	0.50	0.2	1	0.4	0.40	0.5	1	0.2	0.20	0.5
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	1	0.2	0.20	0	1	0.2	0.20	0	1	0.3	0.30	0.3	1	0.4	0.40	0.5
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation.	1	0.1	0.10	-0.2	1	0.1	0.10	-0.2	1	0.1	0.10	0.2	1	0.2	0.20	0.5
5. Life history																
a Density-dependent effects in freshwater affect subsequent survival at sea	1	0.5	0.50	0.5	1	0.5	0.50	0.5	0	0	0.00	0	1	0.3	0.30	0.5
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	0.2	0.2	0.04	0	0.2	0.2	0.04	0	1	0.1	0.10	0	1	0	0.00	0
7. Environment - physical/biological																
a Altered oceanographic conditions have led to changes in migration routes	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.1	0.10	0.1	1	0.2	0.20	0.5
b Reduced prey availability decreases survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.2	0.20	0.5
c UV exposure reduces survival of post-smolts	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.1	0.10	0.1	1	0	0.00	0.5
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	0	0	0.00	0.1
8. Environment - thermal																
a Lower marine temperatures reduce survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.3	0.30	0.2	1	0.4	0.40	0.5

Table 3 (continued)

Hypothesized factor	SFA 15 Northern New Brunswick				SFA 16 Eastern New Brunswick				SFA 17 Prince Edward Island				SFA 18 Gulf Nova Scotia			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
VI. Adult return through estuaries																
2. Aquaculture																
a Presence of salmon in sea-cages disorients returning fish	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5
4. Predation																
a Seal predation in estuaries reduces survival of returning adults	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0	0.00	0.2	1	0.2	0.20	0.5
b Aquaculture sites attract predators, thereby increasing predation on returning adults	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5
6. Environment - chemical																
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	1	0.2	0.20	0	1	0.2	0.20	0	1	0.1	0.10	0	0	0	0.00	0
Plausibility ratings by	G Chaput				G Chaput				D. Cairns				S. O'Neil			
Egg requirement for conservation, millions[a]	71.9				143.5				1.9				23.1			
Weighting factor[f]	1.38				2.76				0.04				0.45			

[a]See Table 2 for footnotes.

Table 4

Factors hypothesized to reduce reproduction or survival of North American populations of Atlantic salmon, and their estimated plausibility by district on the Atlantic coasts of Nova Scotia and and New Brunswick[a]

Hypothesized factor	SFA 19, Atlantic coast & Bras d'Or Lakes, Cape Breton				SFA 20 Eastern Shore, Nova Scotia				SFA 21 Southwestern Nova Scotia				IBOF Inner Bay of Fundy				SW-NB Saint John River and west			
	Area[a]	Degree[b]	Mag [c]	Trend[d]	Area[a]	Degree[b]	Mag [c]	Trend[d]	Area[a]	Degree[b]	Mag [c]	Trend[d]	Area[a]	Degree[b]	Mag [c]	Trend[d]	Area[a]	Degree[b]	Mag [c]	Trend[d]
I. Returning adult to egg																				
1. Fisheries																				
a Fishery removals in estuaries and rivers	1	0.3	0.30	-0.5	1	0.1	0.10	-0.5	1	0.1	0.10	-0.5	0.0	0.0	0.00	-1.0	1	0.3	0.30	-0.5
b Hook-and-release mortality	1	0.1	0.10	0.5	1	0.1	0.10	-0.5	1	0.1	0.10	-0.5	1.0	0.1	0.10	-1.0	1	0	0.00	0
2. Aquaculture																				
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	0.4	0.5	0.20	0.5	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5	1.0	0.1	0.10	0.5	0.12	1	0.12	1
b Aquaculture escapees compete with wild fish for spawning sites	0.4	0.2	0.08	0.5	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5	1.0	0.1	0.10	0.5	0.12	1	0.12	1
c Hatchery-reared salmon have lower spawning success than wild salmon	0.1	0.2	0.02	0	0.5	0.5	0.25	0.5	0.5	0.5	0.25	0.5	0.1	0.2	0.02	-0.5	0.35	0.75	0.26	0
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0.4	0.3	0.12	0.5	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5	1.0	0.1	0.10	0.5	0.3	1	0.30	1
3. Disease																				
a Naturally-occurring disease	1	0.3	0.30	0.5	1	1	1.00	0	1	1	1.00	0	1.0	0.2	0.20	0.5	1	0.3	0.30	0.5
b Disease transmitted from captive or escaped aquaculture fish	0.4	0.3	0.12	0.5	0.1	1	0.10	0.5	0.1	1	0.10	0.5	1.0	0.3	0.30	1.0	0.12	1	0.12	1
7. Environment - physical/biological																				
a Barriers to spawning migration	0.1	0.1	0.01	0	0	1	0.00	0	0	1	0.00	0	0.2	0.8	0.16	0.0	0.47	0.5	0.24	0
b Spawning habitat is limited	1	0.2	0.20	0.5	0	0.25	0.00	0	0	0.25	0.00	0	0.2	0.8	0.16	0.0	1	0.2	0.20	0
c Alterations to discharge patterns reduce access to spawning areas	1	0.1	0.10	0.5	1	0	0.00	0	1	0	0.00	0	0.0	0.0	0.00	0.0	0.47	0.2	0.09	0
8. Environment - thermal																				
a High water temperatures delay access to spawning grounds	1	0.2	0.20	0	1	0	0.00	0.1	1	0	0.00	0.1	1.0	0.2	0.20	0.5	1	0.2	0.20	0.5
II. Egg to hatch																				
2. Aquaculture																				
a Eggs from wild-aquaculture crosses have reduced viability	0.4	1	0.40	0.5	0.1	0.1	0.01	0.5	0.1	0.1	0.01	0.5	0.1	0.4	0.04	0.5	0.12	1	0.12	1
3. Disease																				
a Disease and parasitism reduce egg survival	1	0.1	0.10	0	0	1	0.00	0	0	1	0.00	0	1.0	0.1	0.10	0.0	1	0.1	0.10	0.5
4. Predation																				
a Predation reduces egg survival	1	0.2	0.20	0	1	0	0.00	0	1	0	0.00	0	1.0	0.1	0.10	0.0	1	0.2	0.20	0.5
5. Life history																				
a Reproductive output is reduced because grilse are an increasing fraction of returnees	1	0.4	0.40	0.5	0.2	0.5	0.10	0.5	0.2	0.5	0.10	0.5	1.0	0.0	0.00	0.0	1	0.4	0.40	0.5
6. Environment - chemical																				
a Low pH due to acid precipitation reduces egg survival	1	0.1	0.10	0	0.8	0.8	0.64	0.1	0.8	0.8	0.64	0.1	0.0	0.0	0.00	0.0	1	0.1	0.10	0
7. Environment - physical/biological																				
a Sedimentation processes reduce egg survival	1	0.3	0.30	0.5	0.1	0.5	0.05	0	0.1	0.5	0.05	0	0.2	0.2	0.04	0.0	1	0.2	0.20	0.5
b Alteration of discharge patterns reduces egg survival	1	0.2	0.20	0.5	0.1	0.1	0.01	0	0.1	0.1	0.01	0	0.2	0.2	0.04	0.0	1	0.2	0.20	0.5
III. Hatch to smolt																				
2. Aquaculture																				
a Competition with aquaculture escapees reduces juvenile survival	0.4	0.2	0.08	0.5	0.1	0	0.00	0.5	0.1	0	0.00	0.5	0.2	0.2	0.04	0.5	0.2	0.2	0.04	0.5
3. Disease																				
a Disease and parasitism reduce juvenile survival	1	0.1	0.10	0	0	0.8	0.00	0	0	0.8	0.00	0	1.0	0.1	0.10	0.0	1	0.1	0.10	0
4. Predation																				
a Avian predators reduce juvenile survival	1	0.2	0.20	0	1	0.1	0.10	0.5	1	0.1	0.10	0.5	1.0	0.2	0.20	0.0	1	0.3	0.30	0.5
5. Life history																				
a Precocious maturation reduces the number of juveniles which will become smolts	1	0.2	0.20	0	1	0.1	0.10	0	1	0.1	0.10	0	1.0	0.2	0.20	0.0	1	0.1	0.10	0
b Inter- and intra-specific competition reduces juvenile survival	1	0.2	0.20	0	0.8	0.1	0.08	0.5	0.8	0.1	0.08	0.5	1.0	0.2	0.20	0.0	1	0.3	0.30	0.5
6. Environment - chemical																				
a Toxic chemicals reduce juvenile survival	0.1	0.2	0.02	0	0	1	0.00	0	0	1	0.00	0	0.1	0.3	0.03	0.0	1	0.2	0.20	0.5
b Low pH due to acid precipitation reduces juvenile survival	1	0.1	0.10	0	0.8	0.9	0.72	0.1	0.8	0.9	0.72	0.1	0.0	0.0	0.00	0.0	1	0.1	0.10	0
7. Environment - physical/biological																				
a Sedimentation processes reduce juvenile survival	1	0.2	0.20	0	0	0.5	0.00	0	0	0.5	0.00	0	0.2	0.2	0.04	0.0	1	0.2	0.20	0.5
b Alterations to discharge patterns reduce juvenile survival	1	0.2	0.20	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0	0.2	0.2	0.04	0.5	1	0.3	0.30	0.5
8. Environment - thermal																				
a High summer temperatures reduce juvenile production	1	0.2	0.20	0.5	1	0.1	0.10	0.1	1	0.1	0.10	0.1	1.0	0.2	0.20	0.5	1	0.3	0.30	0.5
b Limited availability of thermal refugia reduces juvenile survival	1	0.2	0.20	0	0.1	0.1	0.01	0.1	0.1	0.1	0.01	0.1	1.0	0.2	0.20	0.5	1	0.2	0.20	0

Table 4 (continued)

Hypothesized factor	SFA 19; Atlantic coast & Bras d'Or Lakes, Cape Breton				SFA 20 Eastern Shore, Nova Scotia				SFA 21 Southwestern Nova Scotia				IBOF Inner Bay of Fundy				SW-NB Saint John River and west			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
IV. Smolt passage through rivers and estuaries																				
2. Aquaculture																				
a Aquaculture escapees increase competition for resources in the estuary	0.4	1	0.40	0.5	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0.5	0.12	1	0.12	1
4. Predation																				
a Bird and seal predation reduces survival of smolts in rivers and estuaries	1	0.5	0.50	0.5	1	0.2	0.20	0.5	1	0.2	0.20	0.5	0.2	0.1	0.02	0.5	1	0.5	0.50	1
b Fish predation reduces survival of smolts in rivers and estuaries	1	0.5	0.50	0	0	0	0.00	0	0	0	0.00	0	0.2	0.1	0.02	0.0	1	0.5	0.50	1
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	0.4	1	0.40	0.5	0.05	0.05	0.00	0.1	0.05	0.05	0.00	0.1	0.1	0.1	0.01	0.5	0.2	1	0.20	1
5. Life history																				
a Density-dependent effects in freshwater affect subsequent survival at sea	1	0.1	0.10	0	0	0.1	0.00	0	0	0.1	0.00	0	1.0	0.0	0.00	-1.0	1	0.1	0.10	0.5
6. Environment - chemical																				
a Toxic chemicals affect smolt migration and reduce survival	0.1	0.3	0.03	0	0	0.8	0.00	0	0	0.8	0.00	0	0.1	0.1	0.01	0.0	1	0.3	0.30	0.5
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	0.1	0.3	0.03	0	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5	0.2	0.1	0.02	0.0	1	0.3	0.30	0.5
c Low pH of rivers decreases survival of descending smolts	0	0.1	0.00	0	0.9	0.5	0.45	0.5	0.9	0.5	0.45	0.5	0.0	0.0	0.00	0.0	1	0.1	0.10	0.5
7. Environment - physical/biological																				
a Dams reduce the number of smolts reaching the estuary	0.1	0.3	0.03	0	0.1	0.2	0.02	0	0.1	0.2	0.02	0	0.1	0.9	0.09	0.0	0.47	0.6	0.28	0.5
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	0.1	0.2	0.02	0.5	0.1	0.2	0.02	0	0.1	0.2	0.02	0	0.2	0.2	0.04	0.0	0.35	0.6	0.21	0.5
c UV exposure in fresh water or in estuaries reduces survival of smolts	1	0.4	0.40	0.5	1	0.2	0.20	0.2	1	0.2	0.20	0.2	1.0	0.1	0.10	0.5	1	0.4	0.40	0.5
8. Environment - thermal																				
a Alterations in spring temperature regimes increase smolt mortality	1	0.1	0.10	0.5	1	0.2	0.20	0	1	0.2	0.20	0	1.0	0.1	0.10	0.5	1	0.1	0.10	0.5
V. Ocean life																				
1. Fisheries																				
a Commercial fisheries in Greenland harvest more salmon than is officially reported	1	0.1	0.10	-0.5	0.5	0.2	0.10	-0.8	0.5	0.2	0.10	-0.8	0.1	0.1	0.01	-0.5	1	0.1	0.10	-0.5
b Undocumented commercial fisheries reduce marine survival	1	0.1	0.10	-0.5	1	0.05	0.05	-0.8	1	0.05	0.05	-0.8	1.0	0.1	0.10	-0.5	1	0.1	0.10	-0.5
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	1	0.5	0.50	0.5	1	1	1.00	0.8	1	1	1.00	0.8	1.0	0.5	0.50	0.5	1	0.5	0.50	0.5
2. Aquaculture																				
a Aquaculture escapees compete with wild salmon for resources in the ocean	1	0.1	0.10	0.5	1	0.1	0.10	0.5	1	0.1	0.10	0.5	1.0	0.3	0.30	0.5	1	0.1	0.10	0.5
3. Disease																				
a Disease and parasites reduce sea survival	1	0.1	0.10	0	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1.0	0.2	0.20	0.0	1	0.1	0.10	0
4. Predation																				
a Predation by other fish reduces marine survival	1	0.2	0.20	0.5	1	0.5	0.50	0	1	0.5	0.50	0	1.0	0.2	0.20	0.0	1	0.2	0.20	0.5
b Predation by birds and marine mammals reduces marine survival	1	0.5	0.50	0.5	1	0.8	0.80	0.2	1	0.8	0.80	0.2	1.0	0.2	0.20	0.5	1	0.5	0.50	0.5
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	1	0.3	0.30	0.5	1	0.8	0.80	0.1	1	0.8	0.80	0.1	1.0	0.4	0.40	-0.5	1	0.3	0.30	0.5
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation	1	0.1	0.10	0.5	1	0.05	0.05	-0.5	1	0.05	0.05	-0.5	1.0	0.4	0.40	1.0	1	0.1	0.10	0
5. Life history																				
a Density-dependent effects in freshwater affect subsequent survival at sea	1	0.2	0.20	0	0.1	0.1	0.01	-0.5	0.1	0.1	0.01	-0.5	1.0	0.0	0.00	-1.0	1	0.2	0.20	0
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	1	0.4	0.40	0	0.2	0.2	0.04	0.5	0.2	0.2	0.04	0.5	1.0	0.0	0.00	0.0	1	0.6	0.60	0
7. Environment - physical/biological																				
a Altered oceanographic conditions have led to changes in migration routes	1	0.2	0.20	0.5	1	0.1	0.10	0.1	1	0.1	0.10	0.1	1.0	0.2	0.20	0.5	1	0.2	0.20	0.5
b Reduced prey availability decreases survival	1	0.3	0.30	0.5	1	0.1	0.10	-0.1	1	0.1	0.10	-0.1	1.0	0.5	0.50	0.5	1	0.2	0.20	0.5
c UV exposure reduces survival of post-smolts	1	0.2	0.20	0.5	1	0.1	0.10	0.5	1	0.1	0.10	0.5	1.0	0.0	0.00	0.5	1	0.2	0.20	0.5
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	0.5	0.1	0.05	0.1	1.0	0.8	0.80	0.8	0.5	0.2	0.10	0.5
8. Environment - thermal																				
a Lower marine temperatures reduce survival	1	0.2	0.20	0.5	1	0.1	0.10	0	1	0.1	0.10	0	1.0	0.0	0.00	-0.5	1	0.2	0.20	0

Table 4 (continued)

Hypothesized factor	SFA 19; Atlantic coast & Bras d'Or Lakes, Cape Breton				SFA 20 Eastern Shore, Nova Scotia				SFA 21 Southwestern Nova Scotia				IBOF Inner Bay of Fundy				SW-NB Saint John River and west			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
VI. Adult return through estuaries																				
2. Aquaculture																				
a Presence of salmon in sea-cages disorients returning fish	0.4	0.5	0.20	0.5	0.1	0.2	0.02	1	0.1	0.1	0.01	1	0.2	0.2	0.04	0.5	0.12	0.5	0.06	0.5
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	0.4	0.8	0.32	0.5	0.1	1	0.10	1	0.1	1	0.10	1	0.6	0.3	0.18	0.5	0.12	0.8	0.10	0.5
4. Predation																				
a Seal predation in estuaries reduces survival of returning adults	1	0.3	0.30	0.5	1	0.2	0.20	0.8	1	0.2	0.20	0.8	1.0	0.2	0.20	0.5	1	0.3	0.30	0.5
b Aquaculture sites attract predators, thereby increasing predation on returning adults	0.4	0.5	0.20	0.5	0.1	0.2	0.02	0.8	0.1	0.2	0.02	0.8	0.2	0.2	0.04	0.5	0.12	0.5	0.06	0.5
6. Environment - chemical																				
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	0.1	0.2	0.02	0.5	0.1	0.1	0.01	0.1	0.1	0.1	0.01	0.1	0.2	0.2	0.04	0.5	0.9	0.2	0.18	0
Plausibility ratings by	L. Marshall				P. Amiro				P. Amiro				S. O'Neil				L. Marshall			
Egg requirement for conservation, millions[e]	71.9				55.2				77.6				30.1				90.6			
Weighting factor[f]	1.38				1.06				1.49				0.58				1.74			

[a]See Table 2 for footnotes.

Table 5

Factors hypothesized to reduce reproduction or survival of North American populations of Atlantic salmon, and their estimated plausibility by district in the northeastern United States[a]

Hypothesized factor	E-Me Washington County, Maine				C-Me Washington Co. to Rockland				W-Me Maine, west of Rockland				NH-Ma New Hampshire & Massachusetts				RI-Ct Rhode Island & Connecticut			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
I. Returning adult to egg																				
1. Fisheries																				
a Fishery removals in estuaries and rivers	0	0	0.00	-1	0	0	0.00	-1	0	0	0.00	-1	0	0	0.00	0	0	0	0.00	0
b Hook-and-release mortality	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
2. Aquaculture																				
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	1	0.1	0.10	0	0.5	0.1	0.05	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
b Aquaculture escapees compete with wild fish for spawning sites	0.9	0.1	0.09	0.2	0.4	0.1	0.04	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
c Hatchery-reared salmon have lower spawning success than wild salmon	0.9	0.1	0.09	0	1	0.1	0.10	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0.9	0.1	0.09	0.2	0.25	0.1	0.03	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																				
a Naturally-occurring disease	1	0	0.00	0.2	1	0	0.00	0.3	1	0	0.00	0	1	0.1	0.10	0	1	0.1	0.10	0
b Disease transmitted from captive or escaped aquaculture fish	1	0.1	0.10	0	1	0.1	0.10	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
7. Environment - physical/biological																				
a Barriers to spawning migration	0.1	0	0.00	0	0.7	0.5	0.35	0	1	0.25	0.25	0	1	0.8	0.80	0	1	0.8	0.80	-0.5
b Spawning habitat is limited	0.1	0	0.00	0	0.1	0	0.00	0	0.2	0.01	0.00	0	1	0.5	0.50	0	0.5	0.5	0.25	-0.5
c Alterations to discharge patterns reduce access to spawning areas	0.1	0	0.00	0	0.1	0.25	0.03	0	0.1	0.25	0.03	0	1	0.1	0.10	0.8	1	0.2	0.20	-0.5
8. Environment - thermal																				
a High water temperatures delay access to spawning grounds	0.05	0.1	0.01	0	0.8	0.1	0.08	0	0.9	0.1	0.09	0	1	0.8	0.80	-0.5	1	0.8	0.80	0
II. Egg to hatch																				
2. Aquaculture																				
a Eggs from wild-aquaculture crosses have reduced viability	0.9	0.01	0.01	0.2	0.5	0.01	0.01	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																				
a Disease and parasitism reduce egg survival	0.9	0.01	0.01	0	1	0.01	0.01	0	1	0.01	0.01	0	1	0.1	0.10	0	1	1	1.00	0
4. Predation																				
a Predation reduces egg survival	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
5. Life history																				
a Reproductive output is reduced because grilse are an increasing fraction of returnees	1	0.25	0.25	0.8	1	0.25	0.25	0.8	1	0.25	0.25	0.8	0	0	0.00	0	0	0	0.00	0
6. Environment - chemical																				
a Low pH due to acid precipitation reduces egg survival	0.25	0.01	0.00	0	0.2	0.01	0.00	0	0.2	0.01	0.00	0	0.5	0.1	0.05	0	0.1	0.1	0.01	0
7. Environment - physical/biological																				
a Sedimentation processes reduce egg survival	0.2	0.5	0.10	0	0.2	0.5	0.10	0	0.2	0.5	0.10	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
b Alteration of discharge patterns reduces egg survival	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
III. Hatch to smolt																				
2. Aquaculture																				
a Competition with aquaculture escapees reduces juvenile survival	1	0.001	0.00	0.5	0.5	0.001	0.00	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																				
a Disease and parasitism reduce juvenile survival	1	0	0.00	0	1	0	0.00	0	1	0	0.00	0	1	0.2	0.20	0	1	0.2	0.20	0
4. Predation																				
a Avian predators reduce juvenile survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.5	0.50	0	1	0.2	0.20	0
5. Life history																				
a Precocious maturation reduces the number of juveniles which will become smolts	0.1	0.01	0.00	0	0.1	0.01	0.00	0	0.1	0.01	0.00	0	0	0	0.00	0	1	0.2	0.20	0
b Inter- and intra-specific competition reduces juvenile survival	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	1	0.8	0.80	0	0.8	0.5	0.40	1
6. Environment - chemical																				
a Toxic chemicals reduce juvenile survival	0.1	0.01	0.00	0	0.5	0.01	0.01	0	0.9	0.01	0.01	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
b Low pH due to acid precipitation reduces juvenile survival	0.1	0.25	0.03	0	0.1	0.25	0.03	0	0.1	0.25	0.03	0	0.5	0.2	0.10	0	0.1	0.1	0.01	0
7. Environment - physical/biological																				
a Sedimentation processes reduce juvenile survival	0.25	0.25	0.06	0	1	0.2	0.20	0	1	0.2	0.20	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
b Alterations to discharge patterns reduce juvenile survival	0	0	0.00	0	0.5	0.2	0.10	0	0.5	0.2	0.10	0	1	0.5	0.50	-0.5	0.5	0.2	0.10	-0.5
8. Environment - thermal																				
a High summer temperatures reduce juvenile production	0.5	0.25	0.13	0.5	0.6	0.25	0.15	0.5	1	0.25	0.25	0.5	0.5	0.5	0.25	0.5	0.5	0.5	0.25	0
b Limited availability of thermal refugia reduces juvenile survival	0.1	0.1	0.01	0	0.1	0.1	0.01	0	0.25	0.1	0.03	0	0.5	0.5	0.25	0	0.5	0.5	0.25	0

Table 5 (continued)

Hypothesized factor	E-Me Washington County, Maine				C-Me Washington Co. to Rockland				W-Me Maine, west of Rockland				NH-Ma New Hampshire & Massachusetts				RI-Ct Rhode Island & Connecticut			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
IV. Smolt passage through rivers and estuaries																				
2. Aquaculture																				
a Aquaculture escapees increase competition for resources in the estuary	1	0.4	0.40	0.5	0.5	0.4	0.20	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
4. Predation																				
a Bird and seal predation reduces survival of smolts in rivers and estuaries	1	0.2	0.20	0.1	1	0.2	0.20	0.1	1	0.25	0.25	0	1	0.5	0.50	0.5	0.1	0.2	0.02	0.5
b Fish predation reduces survival of smolts in rivers and estuaries	1	0.01	0.01	0.1	1	0.2	0.20	0.3	1	0.3	0.30	0.5	1	0.8	0.80	1	1	0.8	0.80	1
c Aquaculture sites attract predators, thereby increasing predation on outgoing smolts	1	0.5	0.50	0.3	0.5	0.5	0.25	0.2	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
5. Life history																				
a Density-dependent effects in freshwater affect subsequent survival at sea	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	1	0.8	0.80	1	1	0.2	0.20	1
6. Environment - chemical																				
a Toxic chemicals affect smolt migration and reduce survival	0.3	0.01	0.00	0	0.3	0.01	0.00	0	0.9	0.01	0.01	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	1	0.4	0.40	0	1	0.4	0.40	0	1	0.4	0.40	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
c Low pH of rivers decreases survival of descending smolts	1	0.25	0.25	0	0.8	0.25	0.20	0	0.4	0.25	0.10	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
7. Environment - physical/biological																				
a Dams reduce the number of smolts reaching the estuary	0.05	0	0.00	0	0.9	0.5	0.45	0	1	0.4	0.40	0	1	0.8	0.80	-0.5	1	0.8	0.80	-0.5
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	0	0	0.00	0	0.2	0.1	0.02	0	0.2	0.1	0.02	0	1	0.2	0.20	0	1	0.2	0.20	-0.5
c UV exposure in fresh water or in estuaries reduces survival of smolts	1	0	0.00	0	1	0	0.00	0	1	0	0.00	0	0	0	0.00	0	0	0	0.00	0
8. Environment - thermal																				
a Alterations in spring temperature regimes increase smolt mortality	1	0.25	0.25	0.2	1	0.25	0.25	0.1	1	0.25	0.25	0.3	1	0.2	0.20	0.5	1	0.1	0.10	0.5
V. Ocean life																				
1. Fisheries																				
a Commercial fisheries in Greenland harvest more salmon than is officially reported	1	0.1	0.10	-0.8	1	0.1	0.10	-0.8	1	0.1	0.10	-0.8	0.2	0.2	0.04	-0.5	0.2	0.2	0.04	-0.5
b Undocumented commercial fisheries reduce marine survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	0.1	0.1	0.01	-0.5	0.1	0.1	0.01	-0.5
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	1	0.3	0.30	0.5	1	0.3	0.30	0.5	1	0.3	0.30	0.5	0	0	0.00	0	0	0	0.00	0
2. Aquaculture																				
a Aquaculture escapees compete with wild salmon for resources in the ocean	1	0.25	0.25	0.2	1	0.25	0.25	0.1	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
3. Disease																				
a Disease and parasites reduce sea survival	1	0.25	0.25	0.2	1	0.25	0.25	0.2	1	0.25	0.25	0	0.1	0.1	0.01	0	0.1	0.1	0.01	0
4. Predation																				
a Predation by other fish reduces marine survival	1	0.1	0.10	0.1	1	0.1	0.10	0.2	1	0.1	0.10	0.3	1	0.5	0.50	0.5	1	0.5	0.50	0
b Predation by birds and marine mammals reduces marine survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.5	0.50	0	1	0.5	0.50	0
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.5	0.50	1	0.1	0.1	0.01	0
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0.5	1	0.1	0.10	0.5
5. Life history																				
a Density-dependent effects in freshwater affect subsequent survival at sea	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0	0.9	0.5	0.45	1	0.2	0.2	0.04	1
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	1	0.5	0.50	0.8	1	0.5	0.50	0.8	1	0.5	0.50	0.8	0	0	0.00	0	0	0	0.00	0
7. Environment - physical/biological																				
a Altered oceanographic conditions have led to changes in migration routes	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.5	0.50	0.5	1	0.1	0.10	0.5	1	0.1	0.10	0.5
b Reduced prey availability decreases survival	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0
c UV exposure reduces survival of post-smolts	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0	1	0.1	0.10	0.2	1	0.1	0.10	0.2
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5	0.5	0.2	0.10	0.5
8. Environment - thermal																				
a Lower marine temperatures reduce survival	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.2	0.20	0.5	1	0.5	0.50	0.5	0.2	0.2	0.04	0.5

Table 5 (continued)

Hypothesized factor	E-Me Washington County, Maine				C-Me Washington Co. to Rockland				W-Me Maine, west of Rockland				NH-Ma New Hampshire & Massachusetts				RI-Ct Rhode Island & Connecticut			
	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]	Area[a]	Degree[b]	Mag.[c]	Trend[d]
VI. Adult return through estuaries																				
2. Aquaculture																				
a Presence of salmon in sea-cages disorients returning fish	1	0.4	0.40	0.5	0.5	0.4	0.20	0.2	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	1	0.4	0.40	0.5	0.5	0.4	0.20	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
4. Predation																				
a Seal predation in estuaries reduces survival of returning adults	1	0.4	0.40	0.2	1	0.4	0.40	0.1	1	0.25	0.25	0	1	0.2	0.20	0	1	0.2	0.20	0
b Aquaculture sites attract predators, thereby increasing predation on returning adults	1	0.4	0.40	0.3	1	0.2	0.20	0.2	0	0	0.00	0	0	0	0.00	0	0	0	0.00	0
6. Environment - chemical																				
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	0	0	0.00	0	0.4	0.1	0.04	0	0.6	0.1	0.06	0	0.1	0.1	0.01	0	0.1	0.1	0.01	-0.5
Plausibility ratings by	E. Baum				E. Baum				E. Baum				D. Kimball				D. Kimball			
Egg requirement for conservation, millions[e]																				
Weighting factor[f]	1.00				1.00				1.00				1.00				1.00			

[a] See Table 2 for footnotes.

Table 6

Plausibility ratings of factors hypothesized to explain the decline of Atlantic salmon in eastern North America. In each cell the position of the dot on the vertical axis indicates Magnitude, and its position on the horizontal axis indicates Trend. Small solid dots indicate that the product of Magnitude and Trend is ≥ 0.05. Large solid dots indicate that the product of Magnitude and Trend is ≥ 0.25.

Hypothesized factor	Q11	Q8,9	Q 5,6,7	Q1,2, 3,10	SFA 15	SFA 16	SFA 17	SFA 18	SFA 19	SFA 20	SFA 21	IBOF	SW-NB	E-Me	C-Me	W-Me	NH-Ma	RI-Ct
I. Returning adult to egg																		
1. Fisheries																		
a Fishery removals in estuaries and rivers	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
b Hook-and-release mortality	○	○	○	•	•	•	○	○	•	○	○	○	○	○	○	○	○	○
2. Aquaculture																		
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	○	○	○	○	○	○	○	○	•	○	○	•	•	○	○	○	○	○
b Aquaculture escapees compete with wild fish for spawning sites	○	○	○	○	○	○	○	○	○	○	○	•	•	○	○	○	○	○
c Hatchery-reared salmon have lower spawning success than wild salmon	○	○	○	○	○	○	○	○	○	•	•	○	○	○	○	○	○	○
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	○	○	○	○	○	○	○	○	•	○	○	•	●	○	○	○	○	○
3. Disease																		
a Naturally-occurring disease	○	○	○	○	○	○	○	•	•	○	○	•	•	○	○	○	○	○
b Disease transmitted from captive or escaped aquaculture fish	○	○	○	○	○	○	○	○	•	•	•	●	•	○	○	○	○	○
7. Environment - physical/biological																		
a Barriers to spawning migration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
b Spawning habitat is limited	○	○	○	○	○	○	●	○	•	○	○	○	○	○	○	○	○	○
c Alterations to discharge patterns reduce access to spawning areas	○	○	○	○	○	○	○	○	•	○	○	○	○	○	○	○	•	○
8. Environment - thermal																		
a High water temperatures delay access to spawning grounds	○	○	○	○	○	○	○	•	○	○	○	•	•	○	○	○	○	○
II. Egg to hatch																		
2. Aquaculture																		
a Eggs from wild-aquaculture crosses have reduced viability	○	○	○	○	○	○	○	○	•	○	○	○	•	○	○	○	○	○
3. Disease																		
a Disease and parasitism reduce egg survival	○	○	○	○	○	○	○	○	○	○	○	○	•	○	○	○	○	○
4. Predation																		
a Predation reduces egg survival	○	○	○	○	○	○	○	○	○	○	○	○	•	○	○	○	○	○
5. Life history																		
a Reproductive output is reduced because grilse are an increasing fraction of returnees	○	○	○	○	○	○	○	○	•	•	•	○	•	•	•	•	○	○
6. Environment - chemical																		
a Low pH due to acid precipitation reduces egg survival	○	○	○	○	○	○	○	○	○	•	•	○	○	○	○	○	○	○
7. Environment - physical/biological																		
a Sedimentation processes reduce egg survival	○	○	○	○	○	○	●	○	•	○	○	○	•	○	○	○	○	○
b Alteration of discharge patterns reduces egg survival	○	○	○	○	○	○	○	○	•	○	○	○	•	○	○	○	○	○
III. Hatch to smolt																		
2. Aquaculture																		
a Competition with aquaculture escapees reduces juvenile survival	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
3. Disease																		
a Disease and parasitism reduce juvenile survival	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
4. Predation																		
a Avian predators reduce juvenile survival	○	○	○	○	○	○	○	○	○	•	•	○	•	○	○	○	○	○
5. Life history																		
a Precocious maturation reduces the number of juveniles which will become smolts	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
b Inter- and intra-specific competition reduces juvenile survival	○	•	•	•	●	●	○	○	○	○	○	○	•	○	○	○	○	●
6. Environment - chemical																		
a Toxic chemicals reduce juvenile survival	○	○	○	○	○	○	○	○	○	○	○	○	•	○	○	○	○	○
b Low pH due to acid precipitation reduces juvenile survival	○	○	○	○	○	○	○	○	○	•	•	○	○	○	○	○	○	○
7. Environment - physical/biological																		
a Sedimentation processes reduce juvenile survival	○	○	○	○	•	○	●	○	○	○	○	○	•	○	○	○	○	○
b Alterations to discharge patterns reduce juvenile survival	○	○	○	○	○	○	○	○	○	○	○	○	•	○	○	○	○	○
8. Environment - thermal																		
a High summer temperatures reduce juvenile production	○	○	○	○	•	•	○	•	•	○	○	•	•	•	•	•	•	○
b Limited availability of thermal refugia reduces juvenile survival	○	○	○	○	○	○	○	•	○	○	○	•	○	○	○	○	○	○

Table 5 (continued)

Hypothesized factor	Q11	Q8,9	Q 5,6,7	Q1,2, 3,10	SFA 15	SFA 16	SFA 17	SFA 18	SFA 19	SFA 20	SFA 21	IBOF	SW-NB	E-Me	C-Me	W-Me	NH-Ma	RI-Ct
IV Smolt passage through rivers and estuaries																		
2 Aquaculture																		
a Aquaculture escapees increase competition for resources in the estuary	○	○	○	○	○	○	○	○	●	○	○	○	●	●	○	○	○	○
4 Predation																		
a Bird and seal predation reduces survival of smolts in rivers and estuaries	○	●	●	●	○	●	○	○	⬤	●	●	○	⬤	○	○	○	○	○
b Fish predation reduces survival of smolts in rivers and estuaries	○	○	○	○	○	○	○	○	○	○	○	○	⬤	○	●	●	⬤	⬤
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	○	○	○	○	○	○	○	○	●	○	○	○	●	●	●	○	○	○
5 Life history																		
a Density-dependent effects in freshwater affect subsequent survival at sea	○	○	○	○	⬤	⬤	○	○	○	○	○	○	●	○	○	○	●	●
6 Environment - chemical																		
a Toxic chemicals affect smolt migration and reduce survival	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	○	○	○	○	○	○	○	○	○	●	●	○	●	○	○	○	○	○
c Low pH of rivers decreases survival of descending smolts	○	○	○	○	○	○	○	○	○	●	●	○	●	○	○	○	○	○
7 Environment - physical/biological																		
a Dams reduce the number of smolts reaching the estuary	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○
c UV exposure in fresh water or in estuaries reduces survival of smolts	○	○	○	○	●	●	○	○	●	○	○	●	●	○	○	○	○	○
8 Environment - thermal																		
a Alterations in spring temperature regimes increase smolt mortality	○	○	○	○	○	●	○	●	●	○	○	●	●	●	○	●	○	●
V. Ocean life																		
1 Fisheries																		
a Commercial fisheries in Greenland harvest more salmon than is officially reported	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
b Undocumented commercial fisheries reduce marine survival	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○
c Natural mortality is higher than presumed and the reduction of abundance is overstated	○	○	○	○	⬤	⬤	○	⬤	⬤	⬤	⬤	⬤	⬤	●	●	●	○	○
2 Aquaculture																		
a Aquaculture escapees compete with wild salmon for resources in the ocean	○	○	○	○	○	○	○	○	●	●	●	●	○	●	○	○	○	○
3 Disease																		
a Disease and parasites reduce sea survival	○	○	○	○	○	○	○	○	○	⬤	⬤	○	○	●	●	○	○	○
4 Predation																		
a Predation by other fish reduces marine survival	○	○	○	○	○	○	○	○	●	○	○	○	●	○	○	○	○	○
b Predation by birds and marine mammals reduces marine survival	⬤	⬤	⬤	⬤	⬤	●	●	●	⬤	●	●	●	⬤	○	○	○	○	○
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance	●	●	●	●	○	○	●	●	●	●	●	○	●	●	●	●		○
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools	○	○	○	○	○	○	○	●	●	○	○	⬤	○	○	○	○	○	○
5 Life history																		
a Density-dependent effects in freshwater affect subsequent survival at sea	○	○	○	○	⬤	⬤	○	●	○	○	○	○	○	○	○	○		○
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	●	●	●	●	○	○	○	○	○	○	○	○	○	⬤	⬤	⬤	○	○
7 Environment - physical/biological																		
a Altered oceanographic conditions have led to changes in migration routes	○	○	○	○	⬤	⬤	○	●	●	○	○	●	●	⬤	⬤	⬤	○	○
b Reduced prey availability decreases survival	○	○	○	○	○	○	○	●	●	○	○	⬤	●	○	○	○	○	○
c UV exposure reduces survival of post-smolts	○	○	○	○	●	●	○	○	●	●	●	○	●	○	○	○	○	○
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	○	○	○	○	○	○	○	○	○	○	○	⬤	●	●	●	●	●	●
8 Environment - thermal																		
a Lower marine temperatures reduce survival	●	●	●	●	○	○	●	●	●	○	○	○	○	●	●	●	○	○
VI. Adult return through estuaries																		
2 Aquaculture																		
a Presence of salmon in sea-cages disorients returning fish	○	○	○	○	○	○	○	○	●			○	○	●	○	○	○	○
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	○	○	○	○	○	○	○	○	●	●	●	●	○	●	○	○	○	○
4 Predation																		
a Seal predation in estuaries reduces survival of returning adults	●	●	●	●	●	●	○	●	●	●	●	●	●	●	○	○	○	○
b Aquaculture sites attract predators, thereby increasing predation on returning adults	○	○	○	○	○	○	○	○	●			○	○	●	○	○	○	○
6 Environment - chemical																		
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Table 7

Means, standard deviations, minima, maxima, and percent exceedances of Magnitude, Trend, and Magnitude x Trend of district scores. Percent exceedance is the percent of districts whose score exceeds the stated value (0.2, 0.5). The top 2 weighted scores are underlined and the top 10 weighted scores are bolded and underlined.

Hypothesized factor	Magnitude								Trend								Magnitude x Trend							
	Raw						Weighted		Raw						Weighted		Raw						Weighted	
	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed.		Mean	Rank
					0.2	0.5							0.2	0.5							0.05	0.25		
I. Returning adult to egg																								
1. Fisheries																								
a Fishery removals in estuaries and rivers	0.22	0.22	0.0	0.5	44	33	0.25	9	-0.38	0.39	-1.0	0.0	0	0	-0.35	62	-0.04	0.06	-0.2	0.0	0	0	-0.04	63
b Hook-and-release mortality	0.07	0.07	0.0	0.2	11	0	0.08	45	0.04	0.40	-1.0	0.5	33	22	0.06	42	0.01	0.05	-0.1	0.1	22	0	0.02	36
2. Aquaculture																								
a Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	0.03	0.06	0.0	0.2	6	0	0.03	59	0.17	0.30	0.0	1.0	28	28	0.20	25	0.02	0.04	0.0	0.1	17	0	0.02	39
b Aquaculture escapees compete with wild fish for spawning sites	0.03	0.04	0.0	0.1	0	0	0.03	60	0.18	0.29	0.0	1.0	33	28	0.21	21	0.01	0.03	0.0	0.1	11	0	0.02	40
c Hatchery-reared salmon have lower spawning success than wild salmon	0.06	0.10	0.0	0.3	17	0	0.06	46	0.03	0.21	-0.5	0.5	11	11	0.05	44	0.01	0.04	0.0	0.1	11	0	0.02	37
d Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0.04	0.08	0.0	0.3	6	0	0.04	57	0.18	0.29	0.0	1.0	33	28	0.21	21	0.02	0.07	0.0	0.3	17	6	0.03	22
3. Disease																								
a Naturally-occurring disease	0.24	0.30	0.0	1.0	39	11	0.26	7	0.13	0.24	-0.2	0.5	39	22	0.13	35	0.03	0.06	0.0	0.2	22	0	0.02	28
b Disease transmitted from captive or escaped aquaculture fish	0.06	0.08	0.0	0.3	6	0	0.06	52	0.21	0.36	-0.1	1.0	33	33	0.21	20	0.03	0.07	0.0	0.3	28	6	0.03	24
7. Environment - physical/biological																								
a Barriers to spawning migration	0.16	0.26	0.0	0.8	33	11	0.15	23	0.03	0.21	-0.5	0.5	11	11	0.02	52	-0.02	0.09	-0.4	0.0	0	0	-0.02	60
b Spawning habitat is limited	0.13	0.17	0.0	0.5	39	11	0.12	33	0.03	0.21	-0.5	0.5	11	11	-0.02	60	0.01	0.07	-0.1	0.3	11	6	0.00	57
c Alterations to discharge patterns reduce access to spawning areas	0.04	0.06	0.0	0.2	6	0	0.05	54	0.04	0.25	-0.5	0.8	11	11	0.03	51	0.00	0.03	-0.1	0.1	11	0	0.00	54
8. Environment - thermal																								
a High water temperatures delay access to spawning grounds	0.15	0.25	0.0	0.8	33	11	0.15	24	0.05	0.25	-0.5	0.5	17	17	0.06	43	-0.01	0.11	-0.4	0.1	17	0	-0.01	58
II. Egg to hatch																								
2. Aquaculture																								
a Eggs from wild-aquaculture crosses have reduced viability	0.03	0.10	0.0	0.4	6	0	0.02	61	0.18	0.29	0.0	1.0	33	28	0.21	21	0.02	0.05	0.0	0.2	11	0	0.02	34
3. Disease																								
a Disease and parasitism reduce egg survival	0.10	0.23	0.0	1.0	6	6	0.10	40	0.03	0.12	0.0	0.5	6	6	0.05	46	0.00	0.01	0.0	0.1	6	0	0.00	50
4. Predation																								
a Predation reduces egg survival	0.10	0.12	0.0	0.5	17	6	0.09	42	0.02	0.13	-0.2	0.5	6	6	0.04	49	0.00	0.02	0.0	0.1	6	0	0.01	48
5. Life history																								
a Reproductive output is reduced because grilse are an increasing fraction of returnees	0.15	0.13	0.0	0.4	39	0	0.16	21	0.28	0.36	-0.5	0.8	56	39	0.29	8	0.06	0.10	-0.2	0.2	39	0	0.06	12
6. Environment - chemical																								
a Low pH due to acid precipitation reduces egg survival	0.10	0.20	0.0	0.6	11	11	0.12	31	0.01	0.03	0.0	0.1	0	0	0.01	53	0.01	0.02	0.0	0.1	11	0	0.01	47
7. Environment - physical/biological																								
a Sedimentation processes reduce egg survival	0.14	0.19	0.0	0.8	28	6	0.12	34	0.13	0.21	0.0	0.5	33	22	0.09	38	0.04	0.10	0.0	0.4	17	6	0.02	35
b Alteration of discharge patterns reduces egg survival	0.03	0.06	0.0	0.2	11	0	0.04	58	0.14	0.23	0.0	0.5	28	28	0.19	28	0.01	0.03	0.0	0.1	11	0	0.01	41
III. Hatch to smolt																								
2. Aquaculture																								
a Competition with aquaculture escapees reduces juvenile survival	0.01	0.02	0.0	0.1	0	0	0.01	63	0.17	0.24	0.0	0.5	33	33	0.18	29	0.00	0.01	0.0	0.0	0	0	0.00	52
3. Disease																								
a Disease and parasitism reduce juvenile survival	0.06	0.07	0.0	0.2	11	0	0.06	51	0.00	0.00	0.0	0.0	0	0	0.00	57	0.00	0.00	0.0	0.0	0	0	0.00	55
4. Predation																								
a Avian predators reduce juvenile survival	0.17	0.10	0.1	0.5	44	6	0.18	16	0.12	0.19	0.0	0.5	33	17	0.14	33	0.02	0.04	0.0	0.2	17	0	0.02	29
5. Life history																								
a Precocious maturation reduces the number of juveniles which will become smolts	0.11	0.08	0.0	0.2	33	0	0.11	35	0.00	0.00	0.0	0.0	0	0	0.00	57	0.00	0.00	0.0	0.0	0	0	0.00	55
b Inter- and intra-specific competition reduces juvenile survival	0.24	0.22	0.0	0.8	61	22	0.29	5	0.28	0.35	-0.5	1.0	56	56	0.33	6	0.07	0.14	-0.3	0.4	39	17	0.10	8
6. Environment - chemical																								
a Toxic chemicals reduce juvenile survival	0.02	0.05	0.0	0.2	6	0	0.02	62	0.04	0.13	0.0	0.5	11	6	0.05	45	0.01	0.02	0.0	0.1	6	0	0.01	46
b Low pH due to acid precipitation reduces juvenile survival	0.11	0.22	0.0	0.7	11	11	0.13	26	0.01	0.03	0.0	0.1	0	0	0.01	53	0.01	0.02	0.0	0.1	11	0	0.01	45
7. Environment - physical/biological																								
a Sedimentation processes reduce juvenile survival	0.11	0.13	0.0	0.5	39	6	0.11	37	0.17	0.28	0.0	1.0	39	22	0.19	27	0.04	0.07	0.0	0.3	17	6	0.03	23
b Alterations to discharge patterns reduce juvenile survival	0.10	0.13	0.0	0.5	28	6	0.13	29	0.04	0.27	-0.5	0.5	17	17	0.04	48	0.00	0.07	-0.3	0.2	6	0	0.00	51
8. Environment - thermal																								
a High summer temperatures reduce juvenile production	0.15	0.08	0.0	0.3	39	0	0.15	22	0.34	0.19	0.0	0.5	83	56	0.38	5	0.06	0.05	0.0	0.2	56	0	0.08	13
b Limited availability of thermal refugia reduces juvenile survival	0.10	0.09	0.0	0.3	33	0	0.10	41	0.09	0.16	0.0	0.5	17	11	0.09	39	0.01	0.03	0.0	0.1	11	0	0.01	44

Table 7 (continued)

Hypothesized factor	Magnitude								Trend								Magnitude x Trend							
	Raw						Weighted		Raw						Weighted		Raw						Weighted	
	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed.		Mean	Rank
					0.2	0.5							0.2	0.5							0.05	0.25		
IV. Smolt passage through rivers and estuaries																								
2. Aquaculture																								
a Aquaculture escapees increase competition for resources in the estuary	0.06	0.13	0.0	0.4	17	0	0.05	53	0.28	0.30	0.0	1.0	50	50	0.26	17	0.03	0.07	0.0	0.2	17	0	0.03	25
4. Predation																								
a Bird and seal predation reduces survival of smolts in rivers and estuaries	0.28	0.19	0.0	0.5	78	39	0.29	4	0.36	0.24	0.0	1.0	78	44	0.36	4	0.11	0.13	0.0	0.5	50	17	0.12	5
b Fish predation reduces survival of smolts in rivers and estuaries	0.24	0.25	0.0	0.8	56	22	0.24	11	0.22	0.39	-0.2	1.0	28	22	0.27	14	0.13	0.27	0.0	0.8	28	17	0.15	2
c Aquaculture sites attract predators, thereby increasing predation on out-going smolts	0.08	0.15	0.0	0.5	22	6	0.07	48	0.18	0.28	0.0	1.0	33	22	0.18	30	0.03	0.07	0.0	0.2	22	0	0.04	21
5. Life history																								
a Density-dependent effects in freshwater affect subsequent survival at sea	0.15	0.22	0.0	0.8	22	17	0.20	12	0.17	0.45	-1.0	1.0	33	33	0.25	18	0.09	0.20	0.0	0.8	28	17	0.12	6
6. Environment - chemical																								
a Toxic chemicals affect smolt migration and reduce survival	0.05	0.09	0.0	0.3	6	0	0.08	44	0.03	0.12	0.0	0.5	6	6	0.05	46	0.01	0.04	0.0	0.2	6	0	0.01	42
b Discharges of steroidogenic compounds compromise the parr-smolt transformation	0.13	0.15	0.0	0.4	22	0	0.16	20	0.09	0.19	0.0	0.5	17	17	0.14	34	0.02	0.04	0.0	0.2	17	0	0.03	27
c Low pH of rivers decreases survival of descending smolts	0.11	0.15	0.0	0.5	28	0	0.12	32	0.08	0.19	0.0	0.5	17	17	0.12	36	0.03	0.07	0.0	0.2	17	0	0.04	19
7. Environment - physical/biological																								
a Dams reduce the number of smolts reaching the estuary	0.18	0.27	0.0	0.8	28	11	0.17	18	-0.01	0.22	-0.5	0.5	17	6	0.01	56	-0.04	0.14	-0.4	0.1	6	0	-0.03	62
b Alterations in discharge regimes reduce the ability of smolts to reach the estuary	0.06	0.07	0.0	0.2	17	0	0.07	47	0.03	0.21	-0.5	0.5	11	11	0.03	50	0.00	0.04	-0.1	0.1	6	0	0.00	49
c UV exposure in fresh water or in estuaries reduces survival of smolts	0.12	0.12	0.0	0.4	33	0	0.14	25	0.23	0.21	0.0	0.5	67	33	0.27	15	0.05	0.06	0.0	0.2	33	0	0.06	14
8. Environment - thermal																								
a Alterations in spring temperature regimes increase smolt mortality	0.15	0.07	0.0	0.3	44	0	0.17	19	0.13	0.35	-0.4	0.5	56	33	0.15	31	0.02	0.04	0.0	0.1	44	0	0.03	26
V. Ocean life																								
1. Fisheries																								
a Commercial fisheries in Greenland harvest more salmon than is officially reported	0.11	0.06	0.0	0.2	22	0	0.11	38	-0.34	0.40	-0.8	0.2	22	0	-0.36	63	-0.02	0.05	-0.1	0.0	0	0	-0.03	61
b Undocumented commercial fisheries reduce marine survival	0.10	0.05	0.0	0.2	17	0	0.11	36	-0.27	0.29	-0.8	0.2	6	0	-0.25	61	-0.02	0.02	-0.1	0.0	0	0	-0.01	59
c Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	0.45	0.26	0.0	1.0	89	67	0.48	1	0.34	0.29	0.0	0.8	61	61	0.40	2	0.20	0.25	0.0	0.8	61	44	0.24	1
2. Aquaculture																								
a Aquaculture escapees compete with wild salmon for resources in the ocean	0.07	0.10	0.0	0.3	17	0	0.07	50	0.23	0.22	0.0	0.5	44	39	0.19	26	0.02	0.04	0.0	0.2	33	0	0.02	31
3. Disease																								
a Disease and parasites reduce sea survival	0.17	0.15	0.0	0.5	39	11	0.18	17	0.08	0.17	0.0	0.5	22	11	0.09	37	0.03	0.08	0.0	0.3	22	11	0.04	18
4. Predation																								
a Predation by other fish reduces marine survival	0.25	0.14	0.1	0.5	83	22	0.28	8	0.04	0.29	-0.5	0.5	28	17	0.09	40	0.01	0.08	-0.1	0.3	17	6	0.02	30
b Predation by birds and marine mammals reduces marine survival	0.43	0.21	0.1	0.8	83	67	0.48	2	0.31	0.23	0.0	0.5	72	56	0.27	11	0.14	0.11	0.0	0.3	72	39	0.14	3
c Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	0.36	0.20	0.0	0.8	94	17	0.36	3	0.31	0.32	-0.5	1.0	67	39	0.28	10	0.11	0.13	-0.2	0.5	78	6	0.10	7
d Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation.	0.12	0.08	0.1	0.4	11	0	0.11	39	0.10	0.38	-0.5	1.0	33	28	-0.01	59	0.03	0.10	0.0	0.4	28	6	0.01	43
5. Life history																								
a Density-dependent effects in freshwater affect subsequent survival at sea	0.15	0.18	0.0	0.5	33	11	0.19	14	0.11	0.49	-1.0	1.0	28	28	0.15	32	0.07	0.13	0.0	0.5	22	17	0.09	10
b Increased proportion of salmon maturing at 1SW reduces egg production of returnees	0.20	0.21	0.0	0.6	50	22	0.20	13	0.28	0.32	0.0	0.8	50	33	0.28	9	0.09	0.15	0.0	0.4	39	17	0.08	11
7. Environment - physical/biological																								
a Altered oceanographic conditions have led to changes in migration routes	0.23	0.17	0.1	0.5	50	28	0.28	6	0.34	0.20	0.1	0.5	61	61	0.37	3	0.10	0.10	0.0	0.3	61	28	0.13	4
b Reduced prey availability decreases survival	0.14	0.10	0.1	0.5	22	6	0.13	27	0.10	0.22	-0.1	0.5	22	22	0.07	41	0.03	0.07	0.0	0.3	22	6	0.02	32
c UV exposure reduces survival of post-smolts	0.11	0.06	0.0	0.2	22	0	0.13	28	0.27	0.22	0.0	0.5	56	44	0.31	7	0.03	0.04	0.0	0.1	33	0	0.05	16
d Local decreases of ocean productivity depress returns due to region-specific fixed migration patterns	0.11	0.18	0.0	0.8	6	6	0.09	43	0.27	0.23	0.1	0.8	39	39	0.27	12	0.06	0.15	0.0	0.6	39	6	0.04	17
8. Environment - thermal																								
a Lower marine temperatures reduce survival	0.21	0.13	0.0	0.5	67	6	0.19	15	0.24	0.28	-0.5	0.5	67	39	0.20	24	0.07	0.07	0.0	0.3	61	6	0.05	15

Table 7 (continued)

Hypothesized factor	Magnitude								Trend								Magnitude x Trend							
	Raw						Weighted		Raw						Weighted		Raw						Weighted	
	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed		Mean	Rank	Mean	SD	Min	Max	% exceed.		Mean	Rank
					0.2	0.5							0.2	0.5							0.05	0.25		
VI. Adult return through estuaries																								
2. Aquaculture																								
a Presence of salmon in sea-cages disorients returning fish	0.05	0.11	0.0	0.4	17	0	0.05	56	0.26	0.35	0.0	1.0	44	39	0.27	13	0.02	0.05	0.0	0.2	11	0	0.02	33
b Captive and escaped aquaculture salmon transmit diseases to returning wild fish	0.08	0.12	0.0	0.4	17	0	0.07	49	0.25	0.35	0.0	1.0	39	39	0.26	16	0.04	0.06	0.0	0.2	28	0	0.04	20
4. Predation																								
a Seal predation in estuaries reduces survival of returning adults	0.23	0.09	0.0	0.4	94	0	0.24	10	0.39	0.25	0.0	0.8	78	67	0.42	1	0.09	0.06	0.0	0.2	72	0	0.09	9
b Aquaculture sites attract predators, thereby increasing predation on returning adults	0.05	0.11	0.0	0.4	17	0	0.05	55	0.25	0.28	0.0	0.8	56	33	0.25	19	0.02	0.04	0.0	0.1	11	0	0.02	38
6. Environment - chemical																								
a Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	0.10	0.16	0.0	0.5	22	11	0.12	30	0.04	0.21	-0.5	0.5	11	11	0.01	55	0.00	0.01	0.0	0.0	0	0	0.00	53

Table 8
Hypotheses related to freshwater life that seek to explain the decline of Atlantic salmon. Hypotheses are given in rank order of Magnitude x Trend.
Rank numbers reflect overall ranking across freshwater, estuarine, and marine phases.

Code	Phase	Category	Hypothesis	Magnitude			Trend			Magnitude x Trend		
				Raw	Weighted		Raw	Weighted		Raw	Weighted	
				Mean	Mean	Rank	Mean	Mean	Rank	Mean	Mean	Rank
III.5.b	Hatch to smolt	Life history	Inter- and intra-specific competition reduces juvenile survival	0.24	0.29	5	0.28	0.33	6	0.07	0.10	8
II.5.a	Egg to hatch	Life history	Reproductive output is reduced because grilse are an increasing fraction of returnees	0.15	0.16	21	0.28	0.28	8	0.06	0.06	12
III.8.a	Hatch to smolt	Envir.-thermal	High summer temperatures reduce juvenile production	0.15	0.15	22	0.34	0.36	5	0.06	0.06	13
I.2.d	Adult to egg	Aquaculture	Spawning success of wild-aquaculture crosses is lower than that of wild-wild crosses	0.04	0.04	57	0.18	0.21	21	0.02	0.03	22
III.7.a	Hatch to smolt	Envir.-phys./biol.	Sedimentation processes reduce juvenile survival	0.11	0.11	37	0.17	0.19	27	0.04	0.03	23
I.3.b	Adult to egg	Disease	Disease transmitted from captive or escaped aquaculture fish	0.06	0.06	52	0.21	0.21	20	0.03	0.03	24
I.3.a	Adult to egg	Disease	Naturally-occurring disease	0.24	0.26	7	0.13	0.13	35	0.03	0.02	28
III.4.a	Hatch to smolt	Predation	Avian predators reduce juvenile survival	0.17	0.18	16	0.12	0.14	33	0.02	0.02	29
II.2.a	Egg to hatch	Aquaculture	Eggs from wild-aquaculture crosses have reduced viability	0.03	0.02	61	0.18	0.21	21	0.02	0.02	34
II.7.a	Egg to hatch	Envir.-phys./biol.	Sedimentation processes reduce egg survival	0.14	0.12	34	0.13	0.09	38	0.04	0.02	35
I.1.b	Adult to egg	Fisheries	Hook-and-release mortality	0.07	0.08	45	0.04	0.06	42	0.01	0.02	36
I.2.c	Adult to egg	Aquaculture	Hatchery-reared salmon have lower spawning success than wild salmon	0.06	0.08	46	0.03	0.05	44	0.01	0.02	37
I.2.a	Adult to egg	Aquaculture	Returning adults which carry aquaculture genes are less fit than fish of pure wild origin	0.03	0.03	59	0.17	0.20	25	0.02	0.02	39
I.2.b	Adult to egg	Aquaculture	Aquaculture escapees compete with wild fish for spawning sites	0.03	0.03	60	0.18	0.21	21	0.01	0.02	40
II.7.b	Egg to hatch	Envir.-phys./biol.	Alteration of discharge patterns reduces egg survival	0.03	0.04	58	0.14	0.19	28	0.01	0.01	41
III.8.b	Hatch to smolt	Envir.-thermal	Limited availability of thermal refugia reduces juvenile survival	0.10	0.10	41	0.09	0.09	39	0.01	0.01	44
III.6.b	Hatch to smolt	Envir.-chemical	Low pH due to acid precipitation reduces juvenile survival	0.11	0.13	26	0.01	0.01	53	0.01	0.01	45
III.6.a	Hatch to smolt	Envir.-chemical	Toxic chemicals reduce juvenile survival	0.02	0.02	62	0.04	0.05	45	0.01	0.01	46
II.6.a	Egg to hatch	Envir.-chemical	Low pH due to acid precipitation reduces egg survival	0.10	0.12	31	0.01	0.01	53	0.01	0.01	47
II.4.a	Egg to hatch	Predation	Predation reduces egg survival	0.10	0.09	42	0.02	0.04	49	0.00	0.01	48
II.3.a	Egg to hatch	Disease	Disease and parasitism reduce egg survival	0.10	0.10	40	0.03	0.05	46	0.00	0.00	50
III.7.b	Hatch to smolt	Envir.-phys./biol.	Alterations to discharge patterns reduce juvenile survival	0.10	0.13	29	0.04	0.04	48	0.00	0.00	51
III.2.a	Hatch to smolt	Aquaculture	Competition with aquaculture escapees reduces juvenile survival	0.01	0.01	63	0.17	0.18	29	0.00	0.00	52
I.7.c	Adult to egg	Envir.-phys./biol.	Alterations to discharge patterns reduce access to spawning areas	0.04	0.05	54	0.04	0.03	51	0.00	0.00	54
III.3.a	Hatch to smolt	Disease	Disease and parasitism reduce juvenile survival	0.06	0.06	51	0.00	0.00	57	0.00	0.00	55
III.5.a	Hatch to smolt	Life history	Precocious maturation reduces the number of juveniles which will become smolts	0.11	0.11	35	0.00	0.00	57	0.00	0.00	55
I.7.b	Adult to egg	Envir.-phys./biol.	Spawning habitat is limited	0.13	0.12	33	0.03	-0.02	60	0.01	0.00	57
I.8.a	Adult to egg	Envir.-temperature	High water temperatures delay access to spawning grounds	0.15	0.15	24	0.05	0.06	43	-0.01	-0.01	58
I.7.a	Adult to egg	Envir.-phys./biol.	Barriers to spawning migration	0.16	0.15	23	0.03	0.02	52	-0.02	-0.02	60
I.1.a	Adult to egg	Fisheries	Fishery removals in estuaries and rivers	0.22	0.25	9	-0.38	-0.35	62	-0.04	-0.04	63

Table 9

Hypotheses related to estuarine life that seek to explain the decline of Atlantic salmon. Hypotheses are given in rank order of Magnitude x Trend. Rank numbers reflect overall ranking across freshwater, estuarine, and marine phases.

Code	Phase	Category	Hypothesis	Magnitude			Trend			Magnitude x Trend		
				Raw	Weighted		Raw	Weighted		Raw	Weighted	
				Mean	Mean	Rank	Mean	Mean	Rank	Mean	Mean	Rank
IV.4.b	Smolt passage	Predation	Fish predation reduces survival of smolts in rivers and estuaries	0.24	0.24	11	0.22	0.27	14	0.13	0.15	2
IV.4.a	Smolt passage	Predation	Bird and seal predation reduces survival of smolts in rivers and estuaries	0.28	0.29	4	0.36	0.36	4	0.11	0.12	5
IV.5.a	Smolt passage	Life history	Density-dependent effects in freshwater affect subsequent survival at sea	0.15	0.20	12	0.17	0.25	18	0.09	0.12	6
VI.4.a	Adults in estuaries	Predation	Seal predation in estuaries reduces survival of returning adults	0.23	0.24	10	0.39	0.42	1	0.09	0.09	9
IV.7.c	Smolt passage	Envir.-phys./biol.	UV exposure in fresh water or in estuaries reduces survival of smolts	0.12	0.14	25	0.23	0.27	15	0.05	0.06	14
IV.6.c	Smolt passage	Envir.-chemical	Low pH of rivers decreases survival of descending smolts	0.11	0.12	32	0.08	0.12	36	0.03	0.04	19
VI.2.b	Adults in estuaries	Aquaculture	Captive and escaped aquaculture salmon transmit diseases to returning wild fish	0.08	0.07	49	0.25	0.26	16	0.04	0.04	20
IV.4.c	Smolt passage	Predation	Aquaculture sites attract predators, thereby increasing predation on out-going smolts	0.08	0.07	48	0.18	0.18	30	0.03	0.04	21
IV.2.a	Smolt passage	Aquaculture	Aquaculture escapees increase competition for resources in the estuary	0.06	0.05	53	0.28	0.26	17	0.03	0.03	25
IV.8.a	Smolt passage	Envir.-thermal	Alterations in spring temperature regimes increase smolt mortality	0.15	0.17	19	0.13	0.15	31	0.02	0.03	26
IV.6.b	Smolt passage	Envir.-chemical	Discharges of steroidogenic compounds compromise the parr-smolt transformation	0.13	0.16	20	0.09	0.14	34	0.02	0.03	27
VI.2.a	Adults in estuaries	Aquaculture	Presence of salmon in sea-cages disorients returning fish	0.05	0.05	56	0.26	0.27	13	0.02	0.02	33
VI.4.b	Adults in estuaries	Predation	Aquaculture sites attract predators, thereby increasing predation on returning adults	0.05	0.05	55	0.25	0.25	19	0.02	0.02	38
IV.6.a	Smolt passage	Envir.-chemical	Toxic chemicals affect smolt migration and reduce survival	0.05	0.08	44	0.03	0.05	46	0.01	0.01	42
IV.7.b	Smolt passage	Envir.-phys./biol.	Alterations in discharge regimes reduce the ability of smolts to reach the estuary	0.06	0.07	47	0.03	0.03	50	0.00	0.00	49
VI.6.a	Adults in estuaries	Envir.-chemical	Pollution in estuaries reduces survival of returning adults or lowers their ability to enter the river	0.10	0.12	30	0.04	0.01	55	0.00	0.00	53
IV.7.a	Smolt passage	Envir.-phys./biol.	Dams reduce the number of smolts reaching the estuary	0.18	0.17	18	-0.01	0.01	56	-0.04	-0.03	62

Table 10

Hypotheses related to marine life that seek to explain the decline of Atlantic salmon. Hypotheses are given in rank order of Magnitude x Trend. Rank numbers reflect overall ranking across freshwater, estuarine, and marine phases.

Code	Phase	Category	Hypothesis	Magnitude			Trend			Magnitude x Trend		
				Raw	Weighted		Raw	Weighted		Raw	Weighted	
				Mean	Mean	Rank	Mean	Mean	Rank	Mean	Mean	Rank
V.1.c	Ocean	Fisheries	Natural mortality after commercial fisheries is higher than presumed, which means that the reduction of pre-fishery abundance is overstated	0.45	0.48	1	0.34	0.40	2	0.20	0.24	1
V.4.b	Ocean	Predation	Predation by birds and marine mammals reduces marine survival	0.43	0.46	2	0.31	0.27	11	0.14	0.14	3
V.7.a	Ocean	Envir.-phys./biol.	Altered oceanographic conditions have led to changes in migration routes	0.23	0.28	6	0.34	0.37	3	0.10	0.13	4
V.4.c	Ocean	Predation	Marine survival has decreased because cooler waters have altered the temperature-mediated balance between predators and prey	0.36	0.35	3	0.31	0.28	10	0.11	0.10	7
V.5.a	Ocean	Life history	Density-dependent effects in freshwater affect subsequent survival at sea	0.15	0.19	14	0.11	0.15	32	0.07	0.09	10
V.5.b	Ocean	Life history	Increased proportion of salmon maturing at 1SW reduces egg production of returnees	0.20	0.20	13	0.28	0.28	9	0.09	0.08	11
V.8.a	Ocean	Envir.-thermal	Lower marine temperatures reduce survival	0.21	0.19	15	0.24	0.20	24	0.07	0.05	15
V.7.c	Ocean	Envir.-phys./biol.	UV exposure reduces survival of post-smolts	0.11	0.13	28	0.27	0.31	7	0.03	0.05	16
V.7.d	Ocean	Envir.-phys./biol.	Local decreases of ocean productivity depress returns due to region specific fixed migration patterns	0.11	0.09	43	0.27	0.27	12	0.06	0.04	17
V.3.a	Ocean	Disease	Disease and parasites reduce sea survival	0.17	0.18	17	0.08	0.09	37	0.03	0.04	18
V.4.a	Ocean	Predation	Predation by other fish reduces marine survival	0.25	0.26	8	0.04	0.09	40	0.01	0.02	30
V.2.a	Ocean	Aquaculture	Aquaculture escapees compete with wild salmon for resources in the ocean	0.07	0.07	50	0.23	0.19	26	0.02	0.02	31
V.7.b	Ocean	Envir.-phys./biol.	Reduced prey availability decreases survival	0.14	0.13	27	0.10	0.07	41	0.03	0.02	32
V.4.d	Ocean	Predation	Marine survival is declining in a self-fueling spiral because post-smolts are too scarce to form schools that protect against predation.	0.12	0.11	39	0.10	-0.01	59	0.03	0.01	43
V.1.b	Ocean	Fisheries	Undocumented commercial fisheries reduce marine survival	0.10	0.11	36	-0.27	-0.25	61	-0.02	-0.01	59
V.1.a	Ocean	Fisheries	Commercial fisheries in Greenland harvest more salmon than is officially reported	0.11	0.11	38	-0.34	-0.36	63	-0.02	-0.03	61

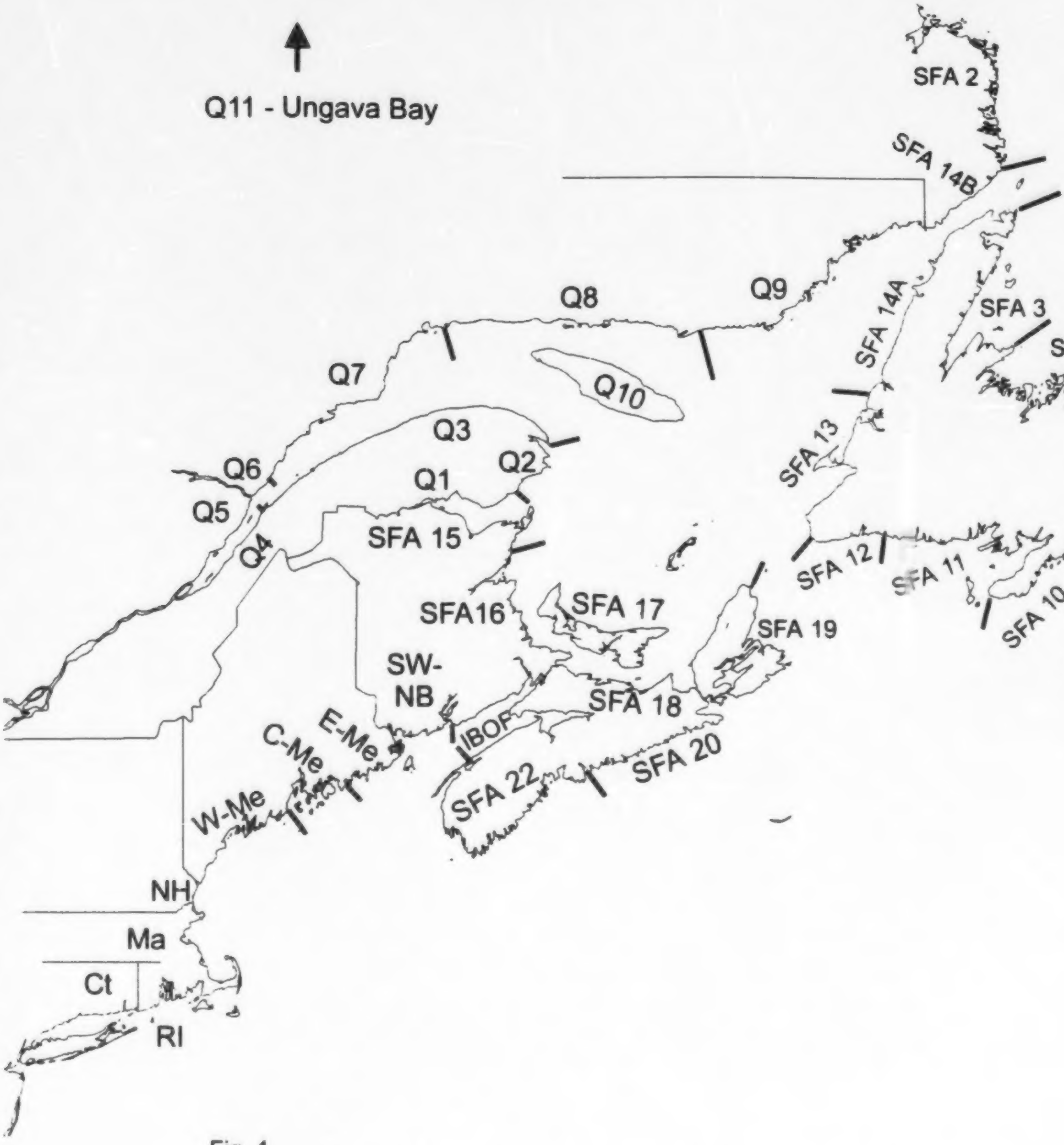
Q11 - Ungava Bay
SFA 2
SFA 14B
Q8
Q9
SFA 14A
SFA 3
SFA 4
Q7
Q10
Q3
Q6
Q2
Q1
Q5
SFA 15
Q4
SFA 13
SFA 5
SFA 6
SFA 7
SFA 12
SFA 11
SFA 8
SFA 17
SFA16
SFA 19
SFA 10
SFA 9
SW-NB
SFA 18
E-Me
C-Me
IBOF
SFA 20
SFA 22
W-Me
NH
Ma
Ct
RI

Fig. 1
Northeastern North America. Salmon management areas are shown.

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